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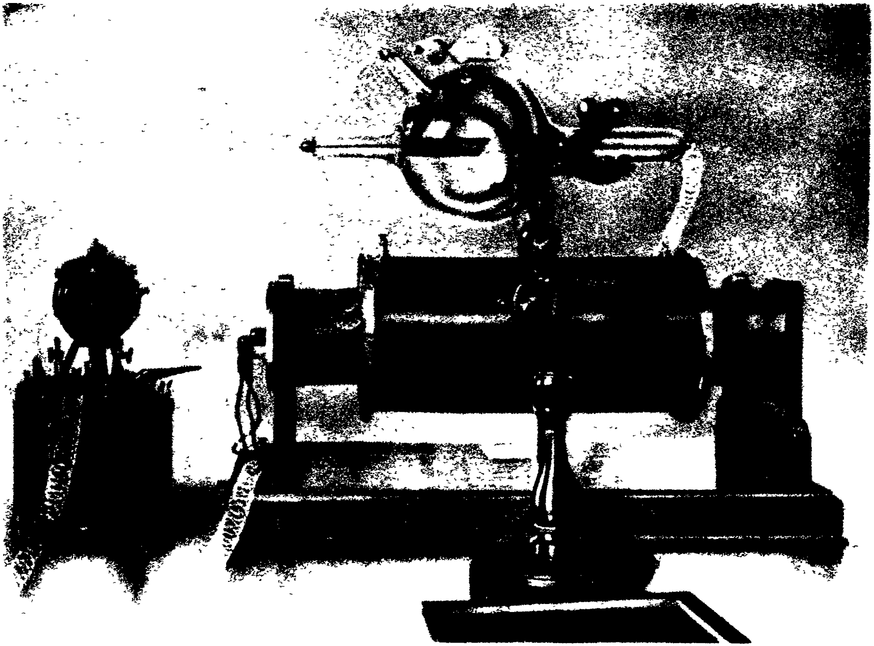
Electricity

and the

Structure of Matter



Electricity
and the
Structure of Matter

by

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LONDON
Oxford University Press
Humphrey Milford
1925

Oxford University Press
London Edinburgh Glasgow Copenhagen
New York Toronto Melbourne Cape Town
Bombay Calcutta Madras Shanghai
Humphrey Milford Publisher to the UNIVERSITY

PRINTED IN ENGLAND

PREFACE

In the first section of this book a slight sketch is given of the history of the subject up to the discovery of the electron—in so far as is necessary to introduce the terms and ideas employed in the later sections. In these the historical method is abandoned ; and, after consideration of a few of the more important of the older applications of electricity, an account is given of several of the principal modern developments, both theoretical and practical.

A glossary of terms is appended.

My thanks are due to my colleague, Dr. R. W. Lawson, who read the MS. and made some valuable suggestions ; to several friends for contributions which are acknowledged in the text ; and to the publishers for help during the course of the work, and for the preparation of the illustrations.

L. S.

THE UNIVERSITY,
SHEFFIELD.
February 1925.

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I

Mainly Historical

The Early Stages

Thales of Miletus, Father of Philosophy and one of the Seven Wise Men of Greece, is credited with performing the first electrical experiment, six hundred years or so before Christ. But for more than twenty centuries this experiment—on the attraction of rubbed amber for light bodies—remained an isolated and neglected fact in physical science.

The beginnings of the allied science of magnetism are lost in the mists of antiquity, but it is certain that the directive property of the lodestone was utilized in the East at a very remote period; its power of attracting iron, and of conferring a like property on iron by rubbing, was also recognized. Not, however, until the sixteenth century of our era were systematic observations made on these analogous, but as yet quite unconnected, classes of phenomena.

Gilbert's discoveries. William Gilbert (1540–1603) of Colchester, by his researches on magnetism and electricity (which latter name he introduced in recognition of the old experiment with ἦλεκτρον = amber) laid the foundations of the two sciences, properly so called, which in due time were to become united in the great modern science of electro-magnetics. The discoveries of Gilbert and his successors reveal further similarities between magnetic and electric phenomena, as well as several points of difference.

These will be realized if we consider briefly the principal results of their investigations.

Gilbert's experiments led him to divide substances into two categories—'electrics' and 'non-electrics'—according as they did or did not acquire, on being rubbed, the property of attracting light bodies. Such experiments can easily be repeated with very simple apparatus. Suspend by means of a silk thread and paper stirrup, after the manner shown in Fig. 1, a light rod—a pencil will do—and bring near to one end of it a stick of sealing-wax, or

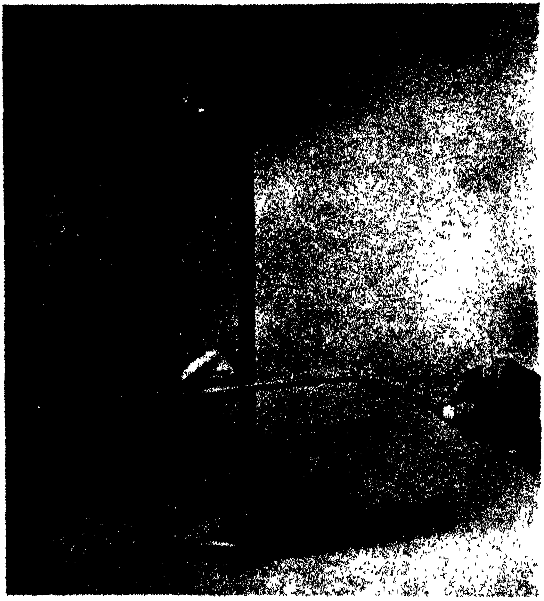

FIG. 1. Apparatus to illustrate electric attraction and repulsion

an ebonite penholder, previously rubbed fairly vigorously with warm flannel. The suspended rod will be strongly attracted by the rubbed body. The same effect can be produced by substituting a rod of glass, rubbed with silk, for the wax or ebonite. If, however, a piece of metal is rubbed and brought up to the suspended body, no effect will be obtained. Sealing-wax, ebonite, and glass are electrics, but metals are non-electrics, to use Gilbert's nomenclature.

Symmer (d. 1763) and Du Fay (1699–1739) found that while all the electrics, when properly rubbed, attracted bodies which had not been so treated, they nevertheless differed in their actions on one another. A glass rod rubbed with silk repelled another glass rod similarly treated (and suspended as in Fig. 1), whereas it attracted a rod of resin excited with flannel. Du Fay was thereby led to postulate two kinds of electricity—'vitreous' and 'resinous'—one or other of which he supposed to be excited on every electric when rubbed with a suitable material. This being assumed, the results of experiments on attraction and repulsion may be summed up by saying, that bodies 'charged' with 'like' electricities repel, while those charged with 'unlike' electricities attract one another.

Electric 'fluids'. This conception of bodies as charged with electricity is a very convenient one, but we must not be too ready to assume that it represents anything more than a simple device to assist in classifying phenomena whose real nature requires further consideration. To give names is not to explain. It is, however, helpful to formulate theories or draw analogies; and the celebrated 'two-fluid' and 'one-fluid' theories of Symmer and Franklin (1706–90) will repay our attention. According to the former, the two electricities are regarded as imponderable fluids ordinarily existing in matter in equal quantities, and so neutralizing one another; but capable of being more or less separated by friction—when dissimilar substances are rubbed together—so as to give rise to an excess of the vitreous fluid in one of the bodies, and a corresponding excess of the resinous fluid in the other. (The two bodies always, in fact, receive dissimilar charges.) Franklin's theory assumes the existence of one electric fluid only. Vitreous, or 'positive' electricity as Franklin called it, corresponds to an excess; and resinous, or 'negative' electricity, to a deficiency of this fluid. On either view the terms positive and negative are appropriate, though there is no reason, or at least there was none in Franklin's day, for singling out one kind of electricity rather than the other as positive. The use of these terms suggests that equal charges of the two kinds should neutralize one another, as in fact they do. The older names, vitreous and resinous, are rather misleading, since it is found that by selecting suitable rubbers, it is possible to excite 'vitreous' electricity on resin, and 'resinous' electricity on glass.

In any case, the 'electric fluid' is not confined to the so-called electrics; indeed the distinction between these and non-electrics is a false one, for electricity can be excited by friction on a non-electric (such as a piece of metal) provided it is supported by an electric, and not held directly in the hand as was usual in the earlier experiments. The non-electrics are in fact conductors of electricity; and the reason they do not show a charge when rubbed is not that no electricity is excited upon them, but that it flows away as fast as it is produced, unless the body is 'insulated' by means of a non-conductor or electric. The true distinction here indicated between the two classes of substances was discovered in 1729 by Stephen Gray. (We shall henceforth speak of electrics as insulators or non-conductors, and of non-electrics as conductors.) The idea of an electric fluid capable of flowing along a conductor is an important one; though at the time to which we are referring, only a rudimentary notion of the electric current was possible.

For the more convenient and copious production of electricity Otto von Guericke (1602–86) of Magdeburg, early in the history of the subject rotated a ball of sulphur, mounted on a spindle, against the skin of the dry hands. In later types of friction machines the sulphur ball was replaced by a glass cylinder or disk provided with a fixed rubber, and also with a 'prime conductor' to collect the positive electricity excited on the glass. In some machines another conductor was added to receive the negative electricity generated on the rubber. With such a machine considerable supplies of electricity of either kind can be obtained, and conveyed, if desired, to other pieces of apparatus.

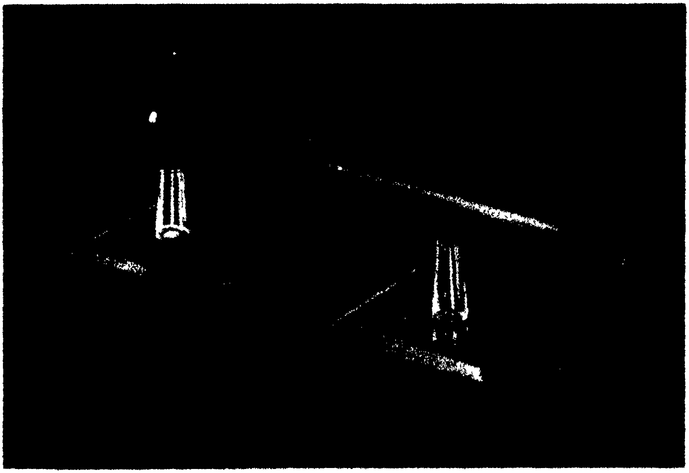

FIG. 2. To illustrate electric induction

Induction. About the middle of the eighteenth century John Canton (1718–72) of Stroud discovered a phenomenon of great importance, the nature of which will be understood from the following considerations. We know that bodies charged with like electricities repel, and bodies charged with unlike electricities attract. Let us assume, according to the two-fluid theory, that an 'uncharged' body really contains equal quantities of the two kinds of electricity, mingled so uniformly that each neutralizes the effect of the other. Now, suppose a charged body to be brought near to an uncharged one. Will the charge of the former cause a separation of the electricities on the latter, by attracting one of them and repelling the other? We may expect such an effect to occur, provided the uncharged body is a conductor—a necessary proviso, for otherwise the electricities would not be able to flow along it, and therefore a separation of them could not be effected in the manner proposed. Canton observed an effect of this kind, which we may visualize in the following way. Suppose an insulated conductor *A* (a metal ball supported by a glass rod), charged with positive electricity, to be brought near an uncharged conductor *B* (also insulated by glass), as shown in Fig. 2. Now, although the charge on *A* remains undiminished, the two ends of *B* will be found to be charged—the end near *A* with electricity unlike that on *A* (negative in this case), and the other end with electricity like that on *A*. These charges are indicated in the figure by the signs − and + respectively. In these circumstances *A*, or rather the charge on *A*, is said to act 'inductively' on *B*; and the charges on *B* are called 'induced' charges.

The attraction of an uncharged body by a charged one is preceded by induction. In Fig. 2 *A* will attract the negative on *B* more powerfully than it will repel the positive (which is farther away); so that, on the whole, the effect will be attractive.

Various methods of obtaining a continuous series of charges by induction have been devised, and machines for this purpose have superseded the older friction machines. An interesting device of this nature is the 'water-dropper', due to Lord Kelvin (1824–

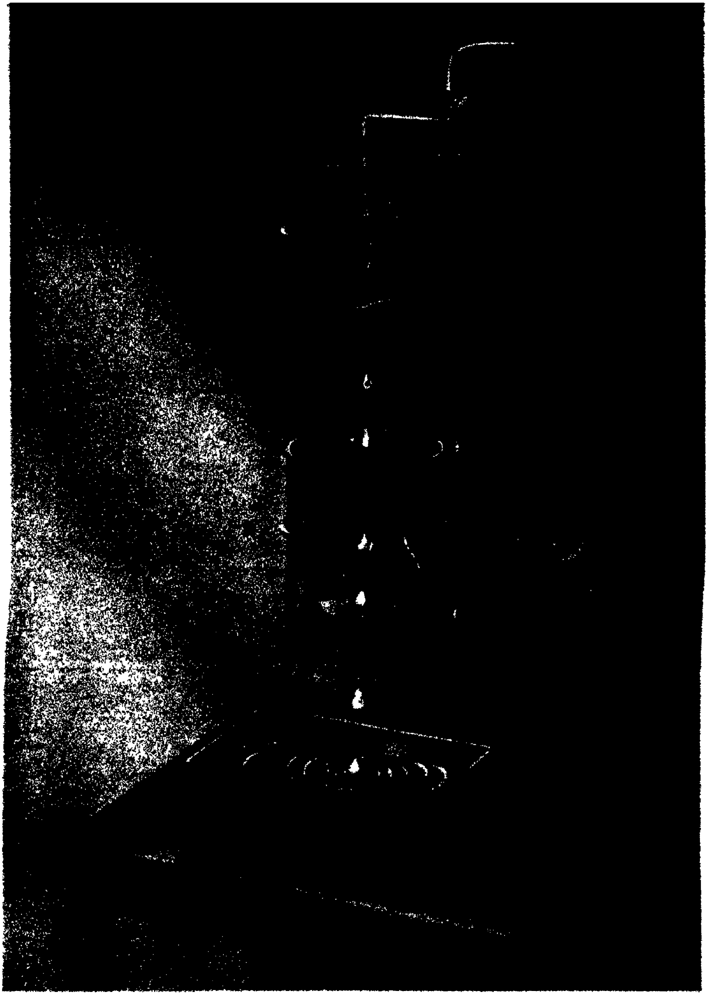

Fig. 3. The single water-dropper, with insulating ebonite standard

NAWAB SALAR JUNG BAHADUR

1907). A jet of water (Fig. 3), breaking into drops, is surrounde by an open metallic cylinder *A* charged negatively (say) by strokin with an ebonite rod previously rubbed with fur. This charge act

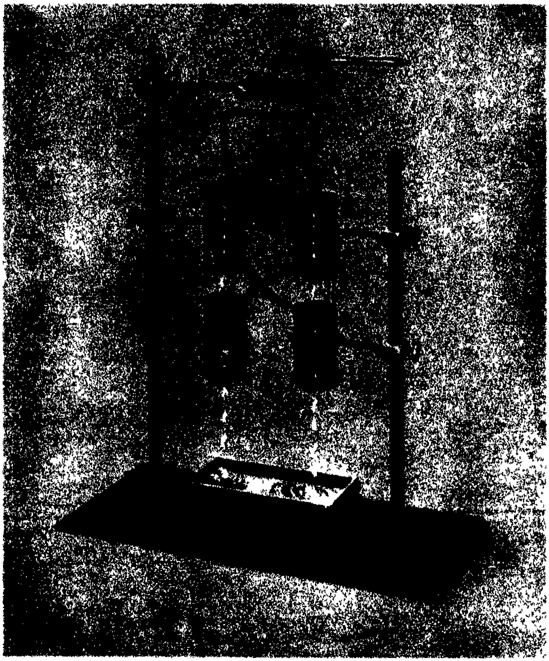

Fig. 4. The double water-dropper

inductively on the jet (which constitutes a conductor, and should be connected to earth); the incipient drop becomes positively charged and negative electricity passes away to earth. When the drop breaks away it carries its positive charge with it until it comes into contact with a metallic gauze, fixed inside a second cylinder *B*.

The electricity immediately flows from the drop to the outside of *B* by reason of self-repulsion; and the now uncharged drop falls away to a sink. The cylinder *B* receives a fresh accession of electricity from each drop, and soon becomes highly charged, though the charge on *A* may be feeble. The arrangement is greatly improved by duplicating the jet and cylinders, and attaching connecting wires, as indicated in Fig. 4. The cylinder *C* then partakes of the charge of *B*, and starts a new action by inducing negative electricity on its jet. This is carried to *D* by the water drops, and is shared by *A*; thus the original charge on *A* becomes augmented. In this way a regenerative principle is brought into play which greatly intensifies the effect. This kind of regenerative action is employed in the various induction machines (of which the 'Wimshurst' is the most popular) and which in principle are not very different from the water-dropper.

Magnetism. We have now left Gilbert and his discoveries far behind; but we must hasten back to examine one or two of his contributions to magnetism, and trace the analogy between them and the electrical phenomena we have been discussing. In the course of his researches on magnetism Gilbert noted that the attractive properties of magnets appeared to be confined to certain regions, which, in magnets of elongated form, were generally found at the ends. At least two such regions or 'poles' exist on every magnet; and while they are alike in their power of attracting iron, they have opposite effects on a pole of another magnet—one of them attracting and the other repelling it. Instead of imitating the electrical nomenclature and naming these unlike poles positive and negative, it is convenient to have regard to the fact that, when freely suspended, the magnet tends to set north and south, and to distinguish the poles as north and south poles accordingly. Very little experimenting is necessary to show that 'like poles repel, and unlike poles attract', this being entirely analogous with the corresponding rule in electricity. Gilbert also discovered the magnetism of the earth, which he regarded as a huge magnet with poles near the geographical poles; he thus elucidated the age-long mystery of the directive tendency of the magnet.

Inductive phenomena, parallel with those exhibited by electricity, also occur in the case of magnetism—a piece of iron, on being brought near the pole of a magnet, itself temporarily acquiring a pair of induced poles.

Again, we may remark that just as the production of one kind of electricity always involves the production of the other kind, so in magnetism, the existence of a north pole necessitates the existence of a corresponding south pole. But while the electricities often reside in different bodies, the two polarities invariably exist on the same magnet. It is impossible, for instance, to isolate a single pole by breaking a magnet in two; such a course would result in the appearance of a new pair of poles at the place of fracture.

The electric current. Towards the end of the eighteenth century a new departure was inaugurated in electricity by the discoveries of Galvani (1737–98) and Volta (1745–1827). Luigi Galvani, a physician of Bologna, noticed that convulsive muscular contractions could be induced in the freshly dissected leg of a frog by touching muscle and nerve with a pair of dissimilar metals, such as copper and iron, the metals themselves being, the while, in contact. A similar effect had been observed more than a century before—a fact unknown to Galvani—by Swammerdam of Amsterdam, but had not been followed up. Alessandro Volta, professor at Pavia, following up the observations of Galvani, which were recognized as electric in origin, investigated the production of electricity by the contact of different substances, and constructed batteries from which continuous currents of electricity could be obtained. Each battery consisted of a succession of elements joined together, an element being composed of a plate of copper and a plate of zinc separated from one another by weak acid or brine, which might be contained in a cup, as in Volta's 'crown of cups', or soaked in a disk of cloth, as in the 'Voltaic pile'. Wires were connected to the initial and final plates (of copper and zinc respectively) which formed the terminals or 'poles' of the battery. The wire attached to the copper tended to acquire a positive charge, that attached to the zinc a negative one; and when they were brought into contact a current of electricity flowed through them. Such a current is not different in nature from that obtained by causing a frictional or induced charge to flow along a wire, but it is continuous and comparatively copious.

It is conventional to speak of the current as flowing from the copper or positive pole of the battery, through the connecting wire, to the zinc or negative pole, in conformity with the notions of the one-fluid theory. We shall see that this particular convention is not a happy one, but it is too late to change it now!

Electrolysis. Instead of joining the terminal wires together, one may dip them into acidulated water, which, being a conductor, will allow the current to flow. In this case the passage of the current is accompanied by decomposition of the water, bubbles of oxygen gas being liberated at the surface of the 'anode' as the wire conveying the current into the liquid is called, and bubbles of hydrogen at the other wire or 'cathode'. This effect, known as 'electrolysis', was discovered about 1800, and in 1805 an explanation was advanced by Grotthus on the following lines. The molecules of the 'electrolyte', or conducting liquid, arrange themselves in lines, under the action of the electric forces exerted by the 'electrodes'—i. e. by the anode and cathode—in a manner shown diagrammatically in Fig. 6, where the atoms or groups of atoms composing the molecules are represented by light and dark circles. The atoms next the electrodes then become detached from their molecules, and a rearrangement takes place throughout the line; the result of this is shown in the next figure, the two 'ions'—as the products of decomposition are called—being ready for liberation at the electrodes. The modern view is that more or less of the molecules concerned in the action are always dissociated in the liquid—that is, split up into their separate ions—one half of these being charged positively and the other half negatively. The former are impelled towards the cathode, and the latter towards the anode, where they give up their charges and become liberated. The movements of these positive and negative charges constitute the current of electricity in the electrolyte.

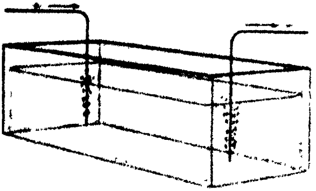

FIG. 5. Electrolysis of water

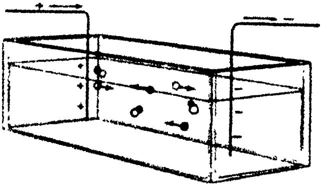

FIG. 6. Hypothesis of Grotthus, position 1

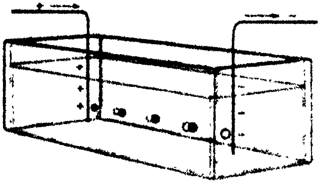

FIG. 7. Hypothesis of Grotthus, position 2. The ions ready for liberation at the electrodes. The molecules will swing round to position 1 under the action of the electric forces

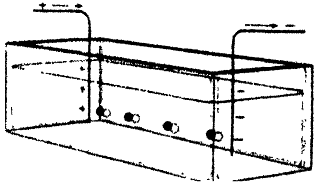

FIG. 8. Illustrating the modern theory of electrolysis

Fig. 9. Lines of force due to a horse-shoe magnet

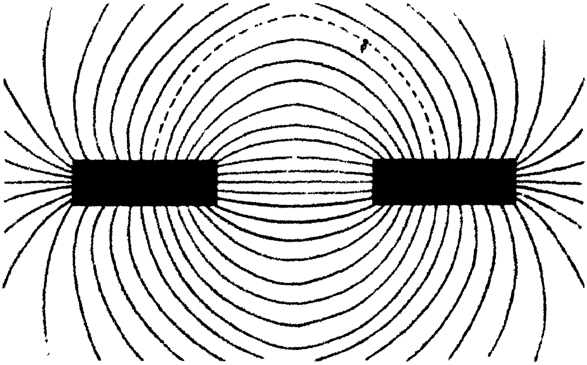

Fig. 10. Diagrammatic representation of the last figure

The time was now ripe for a discovery which was to mark the confluence of the two streams of research which we have hitherto traced under the names of electricity and magnetism. Separately, these were comparatively insignificant; together, they attained remarkable proportions, which, in later times, have been still further expanded by the incorporation of other tributary sciences.

Oersted's discovery. Before the discovery, in 1819, by Oersted (1777–1851), professor at Copenhagen, of the deflection of a magnetic needle by an electric current, few practical applications of importance were forthcoming, if we except the outstanding case of the mariner's compass, and certain results obtained by electrolysis. Nearly all modern applications involve, in one way or another, Oersted's discovery, or the complementary discovery by Faraday of the production of an electric current by means of a moving magnet.

Oersted found, in effect, that an electric current gave rise, in its neighbourhood, to magnetic forces exactly similar to those exerted by an ordinary magnet. Let us examine the effects produced by a magnet a little more closely than we have done hitherto. We can easily do so, experimentally, by the help of some fine iron filings, which should be scattered from a sieve on to a square of cardboard or glass laid on the magnet, as in Fig. 9, which is taken from a photograph of filings scattered on a card placed on the poles *NS* of a horseshoe magnet. The filings will take up a regular formation, like that shown in the figure. Imagine a subsidiary north pole to be placed at any point *P*, Fig. 10. (This pole may be supposed to be on the end of a long, magnetized steel wire, the other end of which, with its south pole, is so far away as to be practically unaffected by the magnet *NS*.) Now, suppose a line, as indicated in the figure, to be drawn through *P* following the configuration of the filings. The pole will be urged along this line—assuming it to be capable of unrestrained motion. We

FIG. 11. Magnetic field due to a current in a straight wire

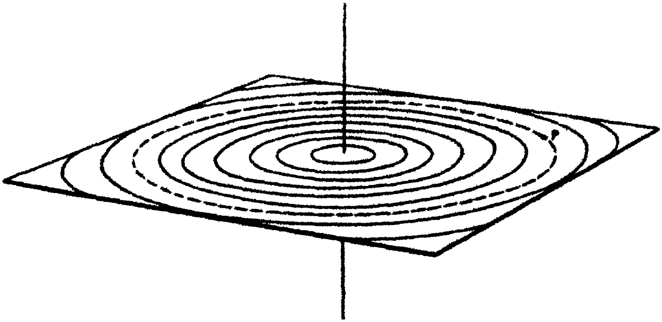

FIG. 12. Diagrammatic representation of the last figure

may state the cause of this in either of two ways—sometimes one way is more convenient, and sometimes the other. We may say that the pole at *P* is attracted by *S* and repelled by *N*; and that the combined effect of these forces is to urge it along the line *NPS*; or we may introduce a new term, and say that in the region surrounding the magnet there exists a 'magnetic field', and that under the influence of this field the pole is urged in the direction marked out by the line *NPS*. This line is called a 'line of force'; and the whole field is visualized for us by the filings, which form up along lines of force in every part of it, and exhibit a kind of grained structure which is characteristic of such fields.

We may now return to Oersted's observation, and describe it by saying that a current of electricity gives rise, in its vicinity, to a magnetic field. This field could be mapped out by filings sprinkled on a card held near the wire conveying the current, and the disposition of its lines of force studied. These would be found to take the form of curves surrounding the wire; and if the wire were straight, these curves would be circles. The accompanying figures show a card (pierced to allow the wire to be passed through its centre) on which filings have been sprinkled. These show the circular formation of the lines. A pole *P*, perfectly free to move, would be urged round and round the particular circle which passes through it.

The electric field. Analogous with the magnetic field is the electric field, which exists in the neighbourhood of a charged body. In such a field a charged particle tends (like a pole in a magnetic field) to move along a definite line, called a line of force. In the case of a sphere charged with electricity, and far removed from all other bodies, the lines of force are straight, and radiate out in all directions from the surface. A charged particle brought into this field would tend to move along one of the lines, either towards or away from the sphere ; or, as we might equally well say, it would be attracted towards or repelled from the sphere in a straight line (according as its charge was unlike or like that on the sphere).

Faraday's discovery on electromotive force. Faraday, in 1831, made a discovery complementary to that of Oersted. We have seen that, according to Oersted, a current flowing in a wire tends to cause a magnetic pole in its vicinity to move along a path called a line of force. If, in fact, we place a conducting circuit and a magnetic pole near to one another, and then make electricity flow round the circuit, the pole, if free, will be caused to move. Suppose, now, we reverse the order of experiment, and, leaving the conducting circuit without any current flowing round it, merely move the magnetic pole (by hand, say). Will any effect be produced on the circuit ? Yes, on performing such an experiment Faraday found that a current of electricity was produced (or induced) in the conducting circuit. The actions of the circuit and pole on one another are thus shown to be reciprocal. If electricity moves round the circuit the pole experiences a tendency to move. Conversely, if the pole moves, the tendency is for electricity to be driven round the circuit. In the latter case, even though the

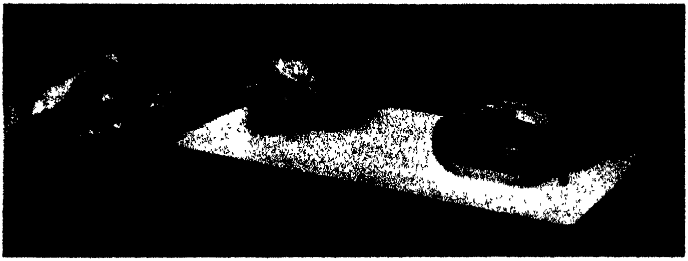

FIG. 13. Illustrating the discoveries of Oersted and Faraday

circuit should be broken by cutting the wire, electricity would still tend to move round it during the motion of the pole. In fact, whether the circuit is complete or not, what is called an 'electromotive force' is induced in the wire by the action of the moving pole. *This, as its name indicates, tends to move electricity; i. e. to cause a current to flow along the wire.* If the wire circuit is continuous a current actually flows; but if not, only a slight movement of electricity is possible, such as to produce a certain accumulation of positive electricity at one end of the wire, and negative electricity at the other. The electromotive force ceases to exist when the movement of the magnetic pole stops, just as in Oersted's experiment the force on the magnetic pole disappears when the current in the wire is cut off.

The phenomena observed by Oersted and Faraday may both be illustrated by a simple apparatus such as that shown in the figure (13). *A* and *B* represent coils of wire connected together so as to form a continuous circuit. In the middle of coil *B*, which is preferably elongated in form, a small magnetic needle is pivoted. This sets north and south, and the coil should be adjusted to lie in the same direction. Now, suppose a bar magnet *NS* to be moved suddenly towards *A* in the direction shown by the dart *S*. According to Faraday's result, a current will be induced in the coil *A*, and this will necessarily flow through *B* as well, since *B* is included in the continuous circuit. But, according to Oersted, this current in *B* will cause the magnetic needle to be deflected. If, now, the magnet *NS* is withdrawn, another current will flow, this time in the opposite direction; and a corresponding deflection of the needle, also in the opposite direction, will take place. The needle will thus respond to every movement of the magnet; and if the connecting wires between *A* and *B* were lengthened, the whole arrangement might be used as a rudimentary electric telegraph.

Electrical quantities. Faraday also made quantitative observations on the decomposition of water by the electric current. We have not yet considered electricity in a quantitative way, nor will it be necessary for our present purpose to go into details as to the measurement of electrical quantities. We can easily see in a general way, however, that the magnitude of the deflection of the needle in Fig. 13 can be regarded as giving an indication of the strength of the current flowing through the coil *B*, since the stronger the current the greater will be the deflection produced. The coil with its pivoted needle forms, when properly arranged, a current-measurer, or galvanometer (so called after Galvani). The current producing a given deflection under given conditions might be called a unit current, or a current of unit strength. We may link up with the idea of unit current that of unit quantity of electricity, by saying that unit current consists of a flow of one unit of electricity per second. The unit of electricity practically adopted is called the 'coulomb',[1] and the corresponding unit of current, the 'ampere'.[2] If electricity passes along a wire at the rate of one coulomb per second, we say that a current of one ampere is flowing; if the rate is 10 coulombs per second, the current is said to be one of 10 amperes, and so on.

We are now in a position to understand Faraday's quantitative of determinations on electrolysis. He found that a definite quantity electricity (about 96,400 coulombs) in passing through the liquid, liberated exactly one gramme of hydrogen; also, when using other compounds of hydrogen instead of water, he obtained an identical result. If we apply the theory of electrolysis, to which we have already referred, to this result, we may say that each gramme of hydrogen, which is in a condition to be liberated by the current, has associated with it 96,400 coulombs of electricity, each individual ion of the hydrogen having its own share. Later on we shall learn the number of hydrogen ions in one gramme; and we shall then be able to determine the quantity of electricity associated with a single ion. Faraday also determined corresponding numbers for other substances; but with these we need not concern ourselves.

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[1] C. A. de Coulomb (1736–1806) of Angoulême, invented an instrument for measuring electric and magnetic attraction.

[2] A. M. Ampère (1775–1836), Professor of Physics in the Collège de France. He investigated induced currents and many other branches of electricity.

An analogy. It will be convenient at this point to consider the close analogy which exists between electricity and an actual fluid, such as water.

Imagine two tanks *AB* (Fig. 14), connected by a narrow pipe, and containing water to the levels *X* and *Y* respectively. Because the pressure at *A* is greater than that at *B*, water will flow along the pipe in the direction indicated by the arrow in the figure. The flow of water in the pipe corresponds to an electric current in a wire; the water itself to the electricity; and the difference of pressure causing the flow of water to the electromotive force driving the current. The unit of electromotive force, corresponding to the units we have already named, is the 'volt' (after Volta). It represents what is sometimes called electrical pressure. Another analogy exists between the current of electricity and the flow of water. Frictional resistance occurs in the water pipe, and tends to restrict the flow, especially if the pipe is long and narrow. Similarly, a wire, particularly if long and thin, offers a resistance to the flow of electricity through it. This resistance depends on the particular material of which the wire is made, as well as on its dimensions; thus iron offers greater resistance to the current than silver or copper. The resistance is a measurable quantity, and is definite in value for a given wire at a given temperature. Its appropriate unit is the 'ohm'.

Ohm's law. We have, then, three measurable quantities relating to a current in a conductor: the current itself, reckoned in amperes; the electromotive force driving the current, in volts; and the resistance imposed on the current by the conductor, in ohms. A simple relation exisiting between these quantities was discovered by G. S. Ohm (1787–1854), professor at Munich, and stated in 1827 in the celebrated law which bears his name. The law states that the electromotive force which drives a current through a conductor of given resistance is equal to the current multiplied by the resistance. Thus an electromotive force of 100 volts will drive a current of 5 amperes through a wire which

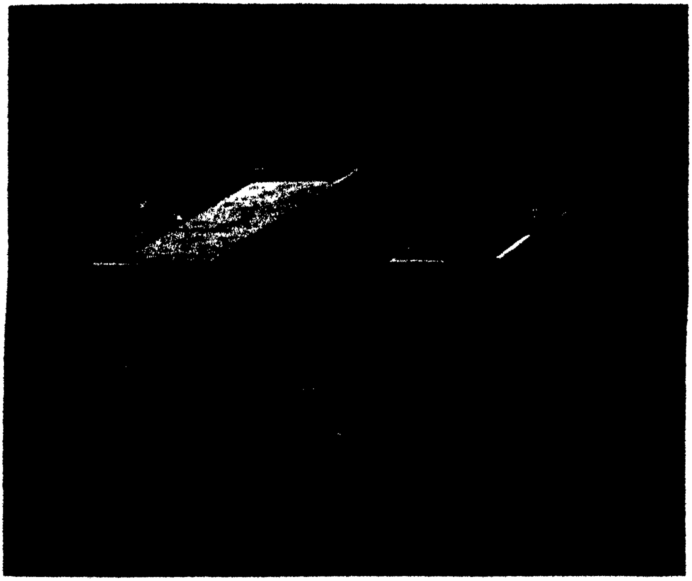

FIG. 14. Illustrating the analogy between a liquid and electricity

has a resistance of 20 ohms. Ohm's law is of fundamental importance for purposes of electrical calculation. It applies not only to the flow of electricity through solids, such as metallic wires, but also to conduction through liquid electrolytes. It does not apply, however, to another case of conduction which, on account of its great importance in relation to modern developments, calls for careful attention—*the conduction of electricity through gases.*

The Discovery of the Electron

The phenomena connected with the conduction of electricity through gases are extremely complex, comprising the electric spark, the arc, and many varied effects obtained by the use of 'vacuum tubes' in which the discharge takes place through gases in a more or less rarefied condition. The processes taking place in such tubes are very complicated; they often give rise to luminous appearances, which vary according to the kind of gas used and the degree of exhaustion attained.

Cathode rays. In 1859 Plücker discovered what are known as 'cathode rays' in a highly exhausted glass tube fitted with two electrodes, or metal wires, by which a current could be made to pass through it. These rays appear to proceed in straight lines from the cathode (which, as in electrolysis, is the electrode by which the current leaves), and they produce a fluorescent glow wherever they strike the glass walls of the tube. A solid obstacle, et up in the tube opposite the cathode, intercepts the rays, and therefore casts a shadow on the walls, though the rays are capable of penetrating very thin metallic foils. A magnet brought near he tube causes a deflection of the rays; this can be detected by a movement of the luminosity which they produce. The nature of the rays was for some time the subject of controversy. Goldstein, who followed up the observations of Plücker, regarded them

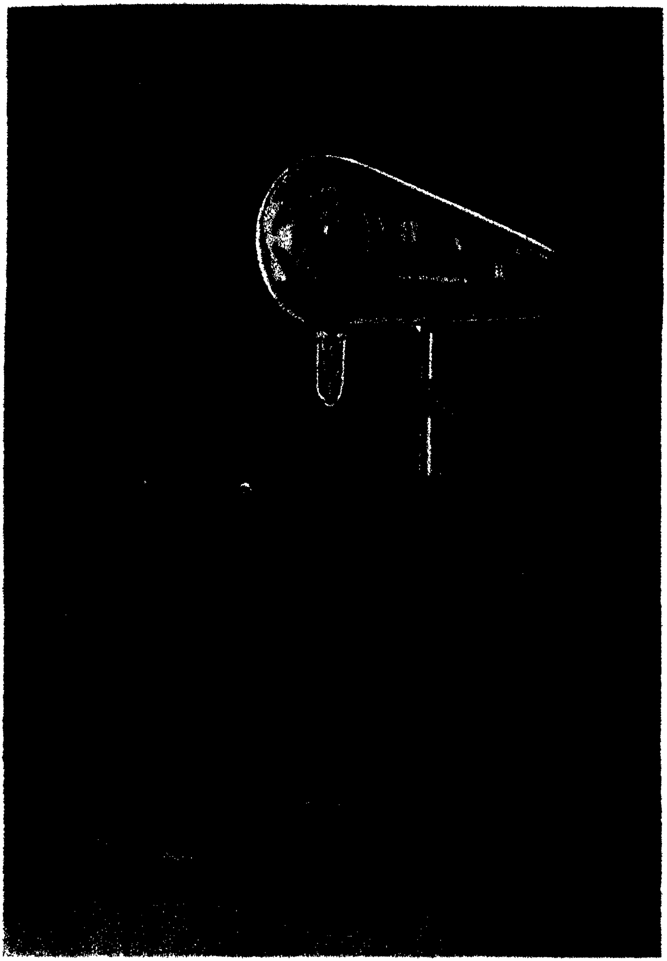

Fig. 15. A discharge tube for the production of cathode rays. The rays proceed from the cathode at the thin end of the tube and cast a shadow of the maltese cross on the other end.

as waves analogous to light; while Crookes believed them to consist of negatively electrified particles projected with great velocity from the cathode. The fact that they could pass through thin foil was not easy to reconcile with the latter theory, even if the particles were as small as molecules; but on the other hand it explained the deflection caused by a magnet; for an electric current, to which such a stream of electrified particles would be equivalent, can actually be so deflected (as can easily be demonstrated by holding a magnet near a loosely suspended flexible wire through which a current is passing), whereas waves like light can not. The second theory now holds the field undisputed, the difficulty regarding penetrating power having been resolved by a remarkable discovery to which our survey will presently lead us.

Assuming that the rays consist of negatively charged particles, it is clear that they ought to be attracted by a positively charged body in or near the tube, and repelled by one negatively charged. This effect can be shown by means of a tube containing a pair of plates capable of holding the necessary charges, and so placed that the rays can pass between them. The rays, under these circumstances, are found to be deflected towards the positive plate.

Electrons. The deflections of a narrow pencil of cathode rays by definite magnetic and electric fields were measured in 1897 by J. J. Thomson, who was able to determine, by means of a fairly simple calculation, the charge carried by a given mass of the particles—or, as we may now call them, 'electrons'. He found this to be very much greater than the charge carried by the same mass of the hydrogen ions in electrolysis, to which we have already referred. If an electron consisted of (say) a hydrogen atom, it would be necessary for it, in order to fit it with Thomson's measurements, to carry a negative charge about 1,800 times as great as the charge on the electrolytic ion. On the other hand, if we assume the charge to be equal to that on the electrolytic ion,

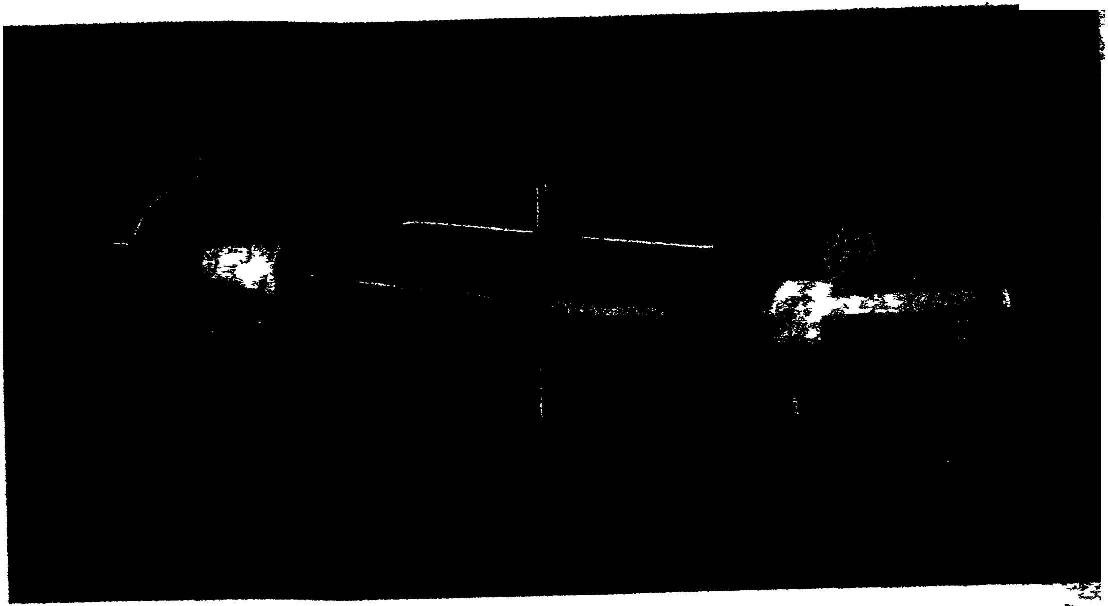

Fig. 16. Tube for the deflection of cathode rays. The rays from the cathode pass through the perforated anode and then between the charged plates A and B. They are slightly deflected towards the positive plate A, and produce a luminous patch on the tube at P.

it follows that the mass of the electron is about 1,800 times less than that of the hydrogen atom.

This was found to be the case by Thomson,[1] who determined the charge on the electron by a method based on an observation of C. T. R. Wilson, that under suitable conditions it was possible to cause a condensation of water vapour to take place on electrified particles, each particle acting as the nucleus of a minute drop of water. In the circumstances of Thomson's experiment it was possible to ascertain the number of drops thus formed, and also the total charge of electricity on the particles, and hence the actual magnitude of the charge on a single particle. This proved to be equal to the charge carried by the electrolytic ion. Thus was the electron shown to be a negatively charged particle 1,800 times lighter than the lightest body hitherto known—the atom of hydrogen.

The cathode rays are found to be identical in their properties in all cases, whatever kind of gas may be present in the tube, and of whatever material the cathode may be made; it may therefore be presumed that if the particles are derived from matter they must form a constituent of all kinds of matter. The atoms of matter should, on this view, consist partly at least of electrons. We cannot, however, suppose them to consist entirely of electrons,

[1] 'All preconceived notions he sets at defiance
By means of some neat and ingenious appliance,
By which he discovers a new law of science
Which no one had ever suspected before.
All the chemists went off into fits;
Some of them thought they were losing their wits,
When quite without warning
(Their theories scorning)
The atom one morning
He broke into bits.'

A. A. R.

since all electrons carry a negative charge; and atoms are, normally, electrically neutral. Each atom must, therefore, contain a quantity of positive electricity equal to the negative electricity contributed by its electrons.

Positive rays.—Atomic fragments. In this connexion it is important to consider another phenomenon which may be observed in a specially constructed discharge tube provided with a perforated cathode. In such a tube it is found that rays pass through the perforations and travel in a direction opposite to that of the cathode rays. They can be deflected by electric and magnetic fields like the cathode rays, but only to a much smaller degree; the deflections, also, are in the opposite direction to what would be expected if they, like the cathode rays, carried negative charges. They are found, in fact, to consist of positively charged particles, and are called positive rays. Their masses are not so small as those of the electrons (which constitute the cathode rays), but are, as nearly as can be ascertained, equal to the masses of atoms or clusters of atoms; and, unlike electrons, they vary according to the kind of gas present in the tube.

How can we explain the existence of such particles? We assume that an atom of matter consists of negatively charged electrons of extremely small mass, together with some other constituent which must necessarily carry enough positive electricity to neutralize the negative charges of the electrons; and further, that under certain circumstances one or more of the electrons can become detached from the atom. Consider the nature of the residue left behind when an electron escapes from an atom. Clearly it must have a positive charge equal to the negative charge on the electron which has left it, for the two when combined formed a neutral body. Again, the mass of the residue should be almost the same as that of the original atom, since the electron which has escaped weighs no more than one part in 1,800 of even the lightest of atoms. Now this specification exactly corresponds with the observed properties of the positive rays. We may, then, sum up by saying that the discharge tube contains atomic fragments—the heavier fragments carrying a positive charge, and the lighter ones a negative charge. Evidently a new and fascinating subject for speculation and research is hereby opened up—the question of the constitution of the atom.

We shall return to the subject in a later section of this book, but we may refer here to two early theories suggested by Thomson and Rutherford. Thomson imagined the atom to consist of a sphere, uniformly charged throughout with positive electricity, and containing the negative electrons arranged in rings or layers within it. Rutherford modified the idea by supposing that the positive electricity, instead of being distributed over the whole atom, was concentrated on a small ‘ nucleus ’ at the centre. The electrons he supposed to circulate in orbits round this nucleus. On this view, the atom is an open structure like a miniature solar system, the lighter atoms having few, and the heavier ones many electrons. The nucleus accounts for nearly all the mass of the atom ; the mass, as well as the positive charge on the nucleus, being greater where the number of electrons is greater.

Either of the theories would suffice for our present purpose ; but it will be well to bear that of Rutherford especially in mind, for it forms the basis of a more recent theory to which we shall refer later.

II

Electric Currents and their Applications

What is electricity? We may, at this stage of our inquiry, try to deal (however inadequately) with the oft-propounded and inevitable question: 'What is electricity?' But, before we attempt an answer, we had better be quite sure what we understand by the question itself. If it means 'What is the ultimate nature of electricity?' we are sure to be disappointed in our search for an answer. We do not even know what is the ultimate nature of matter—we assume in physics that matter really has an objective existence of some sort, but we never try to prove it! If, however, we only understand by the question: 'How can I compare electricity with other things that are more familiar to me—such as vibrations, like those of sound; or fluid, like water or air; or some special state of matter, like the tension of a stretched elastic or the compression of steam in a boiler?'—we may perhaps arrive at a more satisfactory solution.

Let us look at the matter in the light of the theories we considered in the preceding section. According to those theories, an atom of matter is not the indivisible unit it was believed to be a few decades ago. On the contrary, it is a complex—and in the case of the heavier elements an extremely complex—system, capable of being separated, under certain conditions, at least partially into its constituents. Now, these constituents, when separated from one another, exhibit special properties which the atom in its normal or undivided state does not exhibit. We may illustrate this by means of a rough analogy. Common salt (sodium chloride) is a combination of two constituents: a soft, lead-like metal, which bursts into flame when thrown on to water; and poison-gas. Combined, they form 'an indispensable article of diet', and manifest none of the rather alarming properties which characterize them when separated. So with the atom. The special properties of the atomic fragments give rise to phenomena which we find it convenient to call 'electric' phenomena, because some of them were first observed with rubbed electron, or amber. Also, for convenience of reference, we further speak of the phenomena as being caused by 'electricity'. The name was applied long before anything was known of the cause of the phenomena concerned; but there is no reason why we should abandon it now. We can, if we like, apart from using the term in this rather general sense, call the atomic fragments themselves particles of positive or negative electricity, as the case may be; or we may speak of them as particles charged with positive or negative electricity—that is little more than a matter of taste. We know nothing of their ultimate constitution; and our ignorance in this respect is never likely to be dissipated—and I am afraid I can say no more in answer to the question, 'What is electricity?'

Let us use the ideas we have gained for the purpose of elucidating some of the phenomena we meet with in studying electricity; but first, what do we mean by an electrified body, or a body (such as the conductor of Fig. 2) charged with electricity? Simply a body which has an excess or deficiency of one or other kind of atomic fragments. If the body has more than its normal complement of electrons, for instance, it is said to be negatively charged, and it exhibits the properties we associate with that condition; while if it has less than the normal number, it is described as positively charged. In the latter case some of the positive nuclei of its atoms are left without sufficient negative electrons to neutralize them, and the result is a predominance of positive electricity on the body.

In order to render neutral a body thus positively charged, it is only necessary to supply it with enough electrons to make up the deficiency. This can be done—in the absence of opposing influences—by connecting the body, through a conducting wire, to earth; from which, since 'unlike electricities attract', the positive body will be able to acquire the electrons needed to render it neutral. This process is spoken of as 'discharging' the body—an expression which, perhaps, does not very accurately fit the process as we now understand it, but which is nevertheless convenient in use. If the body to be discharged is a conductor, it is only necessary to connect one point of it to earth, for electrons can flow freely all over it and distribute themselves in such a way as to neutralize everywhere the original excess of positive.

Free electrons. The conduction of electricity in a metal is, according to the theory now prevalent, carried on by means of electrons which flow through it, carrying with them, of course, their negative charges. A number of unattached or 'free' electrons exist in a metal in its normal or uncharged condition; these are capable of moving about among the atoms which constitute the body of the metal, and which are themselves open structures, such as are pictured for us by Rutherford's theory. We can, therefore, look upon a 'solid' metal as having an open-work design—full, like Dr. Johnson's 'net', of 'interstitial vacuities' through which fine particles can flow—though not without continual collisions with the impediments which surround them. Some of the atoms must be without their full complement of attached electrons; for if not, the presence of the free ones would render the body, as a whole, negatively charged.

The presence of these free electrons in a metal is indicated, on our present view, by the phenomenon of induction. Consider again the case of the uncharged and insulated conductor *B*, of Fig. 2, which, when brought near the charged body *A*, becomes 'charged by induction', so as to exhibit a negative charge on one end and a positive charge on the other. Now, since these charges are only induced, the body as a whole still remains uncharged; the negative and positive charges upon it being equal to one another in amount. But, under the inductive action of the body *A*, one end of *B* has acquired an excess of electrons, and therefore a negative charge; the other end of *B*, having lost an equal number of electrons, exhibits a corresponding positive charge. This is explained by supposing that electrons, which were previously distributed freely throughout the body, have been drawn towards one end of it—a thing that could not have happened had they been rigidly attached to the atoms constituting the metal.

A conductor, then, is a body more or less of whose electrons are in a free state, though normally distributed uniformly enough to render it neutral throughout. A non-conductor or insulator—a body in which conduction of electricity cannot take place—must be, on the other hand, one whose electrons are all attached to the atoms, none of them being free to roam about from place to place.

Heating effect. Let us consider a little further the conception of a current in a metallic conductor—a copper wire, say—as due to the flow of electrons through a rigid but porous structure. Continual jostling will take place; as though a person should charge, helter-skelter, through a thinly distributed crowd. Two results would follow in such a case: the charger would be impeded by the crowd, and the individuals in the crowd would be agitated by the charger. The first effect in the electrical case is that the metal imposes a resistance to the flow of the current. This resistance, as we noted in Section I, differs in different metals; the effect is considerably greater in iron, for instance, than it is in copper. It depends also on the dimensions of the wire; the longer and thinner the wire, the greater the resistance. The second effect is produced on the conductor by the impacts of the moving electrons with the atoms (or with parts of the atoms) of which it is composed. These—always in a state of commotion, even when no current is passing—are still further agitated by the impacts. Evidently the two effects we are considering will be reciprocally related to one another; that is, the greater the resistance which the metal offers to the electrons, the greater will be the agitation produced by the electrons during their passage amongst the atoms. Now, agitation of the atoms of a body constitutes heat. Thus the passage of the current heats the conductor; and a given current (that is, a given number of electrons flowing per second) produces more heat in a conductor of great or ‘ high ’ resistance than it does in one whose resistance is ‘ low ’. If the electrons could flow quite freely, without encountering any obstacles, no heat would be generated, and the conductor would be without resistance.

In order to produce a maximum heating effect it is necessary to employ a conductor of high resistance, and also to send through it as big a current as possible. On the other hand, if we wish to dissipate as little energy as possible in the form of heat, a good conductor (that is, one of low resistance like copper) should be used.

Practical applications. Many practical applications of the heating effect of a current have been made, ranging from the glow-lamp to the electric tea-kettle. In the circuit of the glow-lamp, conductors of two kinds are employed. Outside the lamp the current is carried by comparatively thick copper wires. The heating effect in these is negligibly small in comparison with the effect produced inside the lamp, where the current is obliged to flow through a very thin filament or wire made of a material of high resistance. Here the heating effect is so intense as to raise the filament to incandescence. It is necessary in practice to protect the filament from oxidation; so it is enclosed in a bulb which is either evacuated or filled with an inert gas, such as nitrogen or argon, which will not attack the filament.

The tea-kettle and its numerous domestic brethren need hardly be described. Their efficacy depends merely on the generation of heat in a wire suitably disposed for the particular purpose in view.

We may note in passing, that good conductors of electricity, like copper, also prove to be good conductors of heat—the free electrons, irrespective of the passage of a current, being very effective in transferring from particle to particle of the body those agitations which constitute heat.

Many of the applications of the current depend on the fact that it produces in its neighbourhood a magnetic field, which, as we saw in Section I, is capable of affecting a magnet. To reduce the phenomenon to its simplest terms, we may note that a moving electron is surrounded by a magnetic field such as to urge a magnetic pole in its vicinity along a certain line of force, which takes the form of a circle surrounding the line along which the electron itself is moving. In the case of a current, or stream of electrons, the lines of force, as indicated by the iron filings of Fig. 11, assume the same form. If, however, the wire conveying the current is bent, say into the shape of a coil, the lines become distorted. They can be visualized by means of iron filings; the disposition of the lines due to a wire in the form of a 'solenoid' or cylindrical spiral approximates to that due to the horse-shoe magnet as illustrated in Fig. 9.

In fact, a solenoid carrying a current acts on external objects just as though it were a bar magnet having north and south poles with the same properties as those of an ordinary magnet. This simulated magnet has the advantage, for many purposes, that its

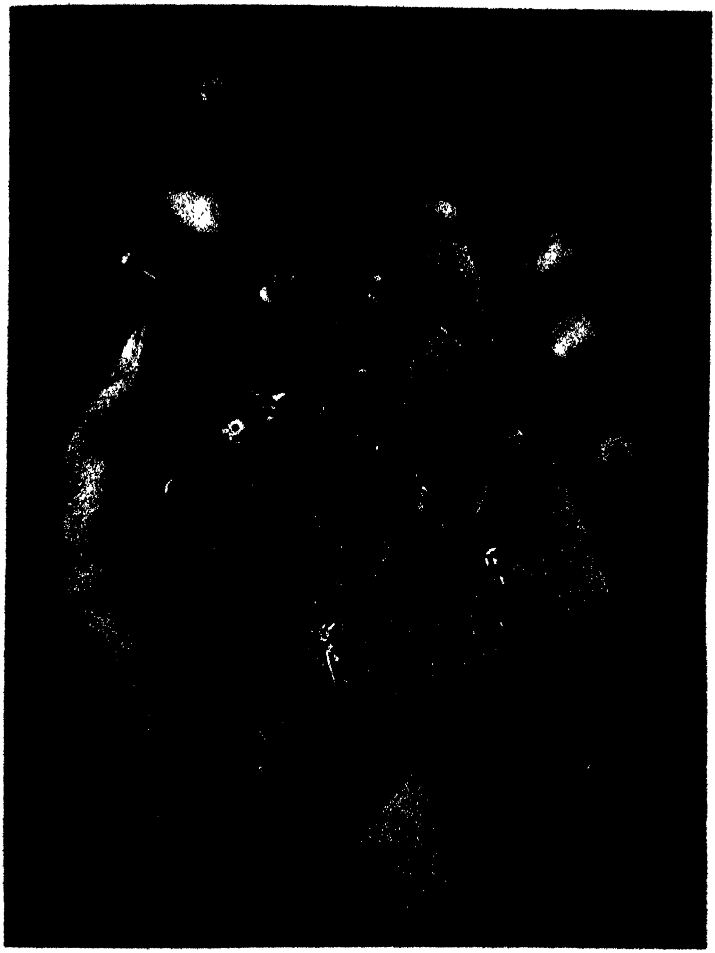

FIG. 17. Electric bell. *A* contact-piece, forming with the armature spring *D* the 'contact-breaker'. The battery and push are shown diagrammatically at *B* and *C*.

strength can be altered at will by varying the current, or reduced to zero by cutting off the current altogether. Its poles can be reversed by reversing the direction of the current.

The electro-magnet. In many applications of the solenoid it is of great advantage to fill the interior with a core of soft iron; this greatly increases the power of the arrangement, which, in this case, is known as an 'electro-magnet'. The increase is due to an inductive effect on the iron, which, if soft, will retain very little of its magnetism when the current is cut off.

An electro-magnet of this kind is used in the construction of the electric bell. In this case the ends of the solenoid are connected to the poles of a battery capable of supplying the necessary current; one of the connecting wires, however, being interrupted at the 'push'—essentially a mere break in the wire, which can be closed by pressure of the finger when it is desired to complete the circuit and ring the bell. The circuit being thus completed, a current flows round the solenoid, and immediately puts the electro-magnet into action. Just opposite the pole of the magnet a piece of iron—called the 'armature'—is held in position by means of a spring. The armature carries the bell clapper, and when the magnet comes into action the armature is attracted and the bell struck. If only a single stroke is required, no other mechanism is necessary; but in the ordinary trembling bell the current, instead of passing straight from the solenoid to the battery and push, is made to pass through the spring of the armature by means of a contact-piece (a small screw) against which the spring normally rests. When the armature is attracted by the magnet, giving a stroke to the bell, the spring leaves the contact-piece, and so breaks the circuit, and the current ceases to flow. The magnet at once loses its power; the spring pulls the armature back to its normal position, and thus makes contact again with the contact-piece; the current flows and again actuates the magnet ; and so on—the bell continuing to ring as long as the push is held down.

The telegraph. An electric bell system, with bell and push separated by a great distance, might play the part of an electric telegraph. It is preferable to replace the bell by a 'sounder', which clicks each time contact is made at the push ; or by a printing mechanism which brings a pen or inked wheel into contact with a continuously moving ribbon of paper—it being as easy, mechanical details apart, to attach a pen, or what not, to the armature as to attach a bell clapper. It is, of course, necessary to arrange for the transmission of signals in both directions ; a simple method by which this can be done is illustrated in the accompanying diagram.

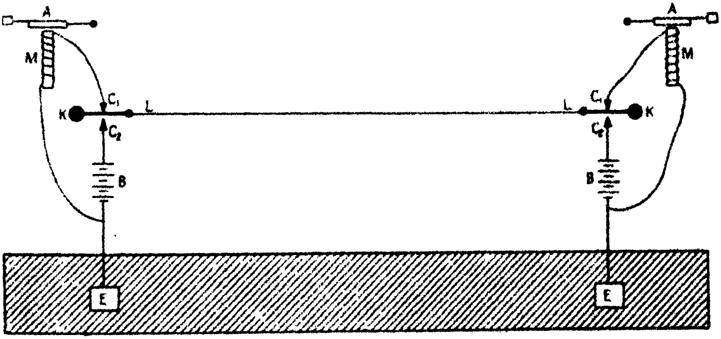

FIG. 18. Simple scheme of connexions for an electric telegraph

At each end of the system we have an electro-magnet M, with armature A (to which may be attached any desired sounding or printing mechanism) and a battery B, together with two metal studs C_1 C_2, the various parts being disposed and connected as shown in the figure. Between the studs, and normally resting against the upper one, C_1, is a spring lever K, which, on being depressed by the hand, leaves C_1, and makes contact with C_2. K is connected to the line wire L which joins the two stations. Instead of a second line wire (such as would be used in our crude electric bell telegraph) the earth is utilized ; each battery being connected, as shown, to a metal plate E sunk in the ground. In the normal state of the apparatus as represented in the figure no current can flow from either battery, for in each case contact is broken at C_2. Suppose, however, the key K, at the left-hand station, to be depressed so as to make contact with C_2 instead of C_1. The left-hand battery will send a current through C_2 and L to the distant station ; then, by way of C_1, through the coil M, and down to the earth-plate E. (We may imagine the earth to complete the circuit—between the two plates—leading back to the left-hand battery B.) Thus, when the key is depressed, the magnet at the distant station is actuated, and the required signal given. The whole apparatus is symmetrical, so that signals can be sent equally well from either end.

As regards the function of the earth in this arrangement, we can hardly suppose that the actual current which flows along the line wire finds its way back to the sending battery. The earth, however, is a conductor ; it contains, like all other conductors, free electrons which can, so to speak, be pumped up by the battery, and propelled along the line wire, to be discharged to earth at the other end, just as water could be pumped from the sea and forced through a long pipe, and then, after being made to drive a turbine, be discharged into the sea again.

The telephone. Let us suppose that instead of telegraphic signals, consisting of distinct taps, or dots marked by a pen, we wish to transmit speech ; that is, to reproduce sound waves at the distant or receiving station. We will assume, for simplicity, that we wish to transmit a musical note of definite pitch ; exactly similar principles will, of course, apply to the transmission of spoken words.

Our problem is this: given a set of sound waves of definite frequency [1]—such waves (say) as would be given out by a voice singing 'middle C'—at the transmitting end of the line wire, to produce a similar set of waves of the same frequency in the air near the receiving end of the line. If we can do this, a listener at the receiving end, on whose ears the waves impinge, will hear a reproduction of the sound of the voice speaking or singing at the other end of the system.

Consider for a moment the receiving apparatus *M*, *A* of the telegraph of Fig. 18, and imagine the armature *A* to be replaced by a disk of thin iron fitted to a ring or round box after the manner of a drum-head, the middle of this disk being very near the end of the iron core of the magnet *M*, but not quite touching it. Now suppose it possible to transmit through the line wire a quick succession of momentary currents. Each time one of these currents passes, the magnet will pull towards itself the centre of the iron disk or diaphragm, thus causing the diaphragm to bulge slightly; when the current ceases, the diaphragm will spring back to its original position. Thus, as the currents succeed one another, a corresponding succession of movements will take place in the diaphragm, which, in turn, will produce waves in the adjoining air. These waves, falling on the ear of a listener, will give rise to that particular sound-sensation which corresponds to the frequency of these movements. Our problem now narrows down to this: how to transmit through the line wire a succession of momentary currents having a frequency equal to that of the sound waves we wish to reproduce.

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[1] Sound is conveyed to the ear by air-waves, which are produced by the vibrations of the sounding body. The pitch of the sound depends on the 'frequency', or number of waves generated per second.

Imagine a circuit arranged in the manner shown in the accompanying figure, where *MA* represents the receiving instrument we have already considered, *LL* a double line, *B* a battery, and *C* an arrangement consisting of a fixed contact-stud joined to the battery and a very light flexible metal tongue or reed fixed at one end to the line wire as shown; the reed being very nearly in contact with the stud. Now, suppose sound waves to impinge on the reed so as to set it into vibration. Each time it touches the contact-stud (which it will do once at each vibration) the electric circuit will be completed, and a transient current will pass to the distant station and actuate the magnet *M*. Thus for each vibration of the reed (which will keep time with the sound waves falling on it) a movement of the diaphragm at the receiving end will take place; and thus the sound falling on the reed will be reproduced.

This imaginary arrangement resembles in general outline the actual method adopted for telephonic communication. Instead of the vibrating reed, a 'microphone' is joined up in circuit. A common form of this consists essentially of two conducting carbon plates near to, and opposite, one another; the small space between them being filled with conducting granules of carbon. One of the plates is fixed, and the other connected to a diaphragm like that of the receiving instrument. When spoken to, this diaphragm vibrates; and, at each vibration, varies the pressure between the plates and granules. This, by varying the resistance of the microphone, produces corresponding variations in the current, and these affect the receiver in the manner we have described. Many practical details necessary for long-distance transmission from both ends of the system must necessarily be omitted from this short account.

Let us now examine a little more closely—in the light of the notions we have gained of the electrons—the mutual effects of a magnet and a current of electricity. [We may recall at this point

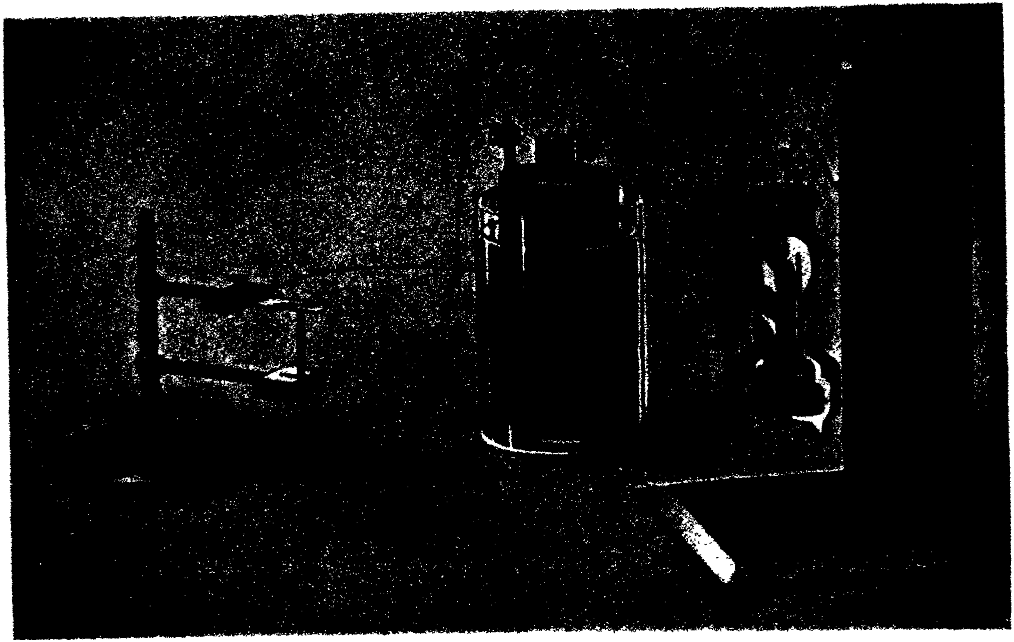

Fig. 19. Sketch-diagram to illustrate the principle of the telephone

the discoveries of Oersted and Faraday referred to on pages 21 and 25.]

Conductor in magnetic field. Suppose a rod of copper, *AB*, Fig. 20, to be held between the poles *NS* of a magnet shaped like the letter U. Consider a free electron *E* in the middle of the rod, midway also between the poles of the magnet. So long as everything is at rest (we will neglect the spasmodic motions of *E* which are always taking place) the magnet has no effect on the electron. But, now, suppose the rod to be moved quickly down towards the bend of the *U*—or, what comes to the same thing, let the magnet be moved up in the opposite direction, while the rod remains at rest. At once, mutual action between the electron and the poles comes into play. The effect is to urge the electron along the rod in the direction *B* to *A*.

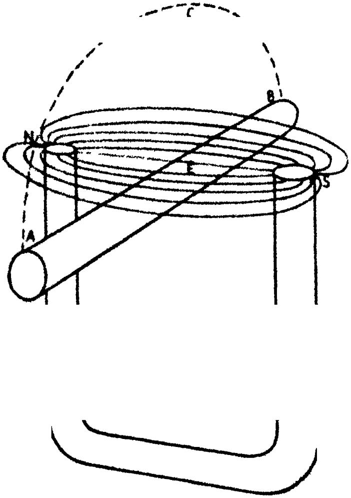

FIG. 20. Conductor in magnetic field

We may put the matter in a slightly different way. The diagram shows a series of magnetic lines of force, extending from *N* to *S*. These represent part of the magnetic field of the magnet. The rod *AB* lies laterally across the lines. They do not affect it so long as no motion occurs. But if either magnet or rod moves so as to cause the rod to sweep across the lines an electromotive force is set up in the rod such as to urge the electrons within it to move along in one direction or the other, according to the direction in which the lines are swept over by the rod. It is immaterial whether the rod sweeps past the lines or the lines past the rod; all that matters is the mutual or relative motion of the two. If the two ends of the rod are joined by a wire (represented, say, by the dotted line *C* in the diagram) which, of course, also contains free electrons, the result of the motion will be a circulation of electrons round the entire circuit *BAC*. In fact, in accordance with Faraday's discovery, an electric current will be generated in the circuit *BAC* by the displacement of the conductor *AB* in the magnetic field due to the poles *NS*.

The dynamo. The arrangement constitutes the germ of the dynamo—the machine which, in present-day practice, supplies electric current for all purposes where large output is required. We must not suppose, however, that a current can be obtained by such an arrangement without an expenditure of mechanical energy, in working it, at least equal to the energy in the current produced. For, although there is no material contact between the conductor and the magnet, yet, when the conductor is moved across the field it meets with a resistance to motion which would not exist if the magnet were not there.

In this connexion a rather curious experiment may be performed if a very powerful electro-magnet, bent so as to bring its poles opposite to one another, is available. A plate of copper, held in the hands between the poles, but not touching them, is quite unaffected by the magnet so long as it is held still; but if it is suddenly snatched away from the magnet a considerable resistance is felt, as though some invisible agency were trying to prevent its motion—which indeed is the case. If one could see the electrons in the plate while it is being moved rapidly through the strong magnetic field which exists between the poles, they would be found to be circulating energetically in closed curves within the metal, and continually bombarding the atoms of the metal, and thus raising the temperature of the plate. The energy expended in moving the plate against the resistance it encounters goes to produce these electron currents and the heat which they generate.

In one of the common forms of the dynamo the conductors—of which there must be many to give an adequate output of current—are arranged on a drum which can be rotated rapidly by an engine between the poles of an electro-magnet. This magnet is supplied with current from the dynamo itself; in some cases the whole and in others a part of the current which is generated being made to pass through coils wound on the limbs of the magnet. A certain amount of permanent magnetism always exists in the magnet, otherwise the machine could not begin to produce a current—for there would be no magnetic field for the conductors to traverse. Quite a small field, due to the permanent magnetism, is sufficient to start the action and cause a small current to flow through the magnet coils; this increases the field, which, in its turn, causes an increase in the current, and so on, till a maximum value is reached.

A general idea of the arrangement of the parts in a simple form of machine can be got from Fig. 21, which shows diagrammatically a dynamo with a single rotating conductor *ab*, bent into rectangular shape, and an electro-magnet with coils through which the whole current is made to pass. The ends of the conductor are attached to the segments of a split ring *A*, and the whole rotates on a spindle (not drawn in the diagram) about the axis *AB* in the direction shown by the curved arrow. The side *a* of the conductor, in moving up through the magnetic field between the poles *N* and *S*, becomes the seat of an electromotive force which drives a current in the direction shown by the dart. At the same time a current is produced in *b* in the direction indicated; thus *a* and *b* conspire to drive a current through the whole circuit comprising the contact brushes *c*, *d* (which press on the segments of the split ring as it rotates), the coils of the electro-magnet, and the 'external circuit' indicated at *E*—this, of course, representing any circuit in which the current is to be employed. After half a rotation *a* and *b* will have changed places; but the same figure exactly represents the new position, and the current passes as before. In an actual machine many conductors like *ab* are used, the ring to which their ends are fixed being split into many sections. They are connected together in such a way as to ensure

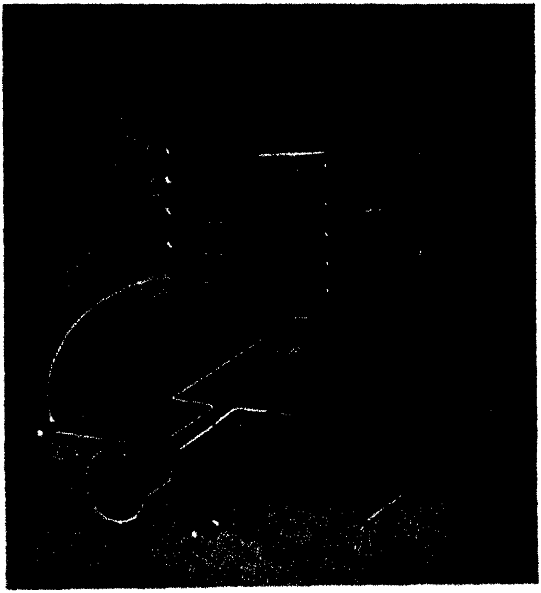

FIG. 21. Sketch-diagram of simple dynamo with single rotating conductor *a b*. The external circuit is indicated at *E*

that the current generated in each shall play its part in the general result.

In some machines the conductors and contact brushes are so arranged as to produce a current which continually reverses in direction. Such a machine is called an ‘ alternator ’, the former type being known as a ‘ direct current ’ machine. In the case of the alternator it is clear that a different arrangement must be made for exciting the electro-magnet, for a current subject to constant reversals of direction would be useless for that purpose. A subsidiary direct current machine may be used to provide the necessary current. In many alternators the magnet is made with several pairs of poles, north and south poles being arranged alternately round a ring or drum, which is frequently made to revolve instead of the conductors—these being fixed in position.

It is easy to see that an alternating current is applicable to those cases which, like the glow-lamp and tea-kettle, depend on the heating effect produced in a wire by the jostling of the electrons as they flow along it. For such an effect cannot depend on the direction in which the electrons pass, nor on the maintenance of a constant direction—a backward and forward motion of the stream of electrons is as effective as a constant flow in one direction.

The electric motor. We have been dealing with the production of a current of electricity by moving a conductor in a magnetic field ; but the converse phenomenon is also of great theoretical and practical importance.

Let us revert to the figure on p. 50, which illustrates a conductor in a magnetic field. In the case already considered we applied mechanical force to the conductor, and obtained a current in it. Now let us take the same apparatus, and pass a current through the conductor by connecting it up to a battery or dynamo. The result will be a mechanical force on the conductor tending to move it up or down (assuming the arrangement to be that shown in the diagram) according to the direction in which we pass the current. Thus we may either apply force and gain current, or apply current and gain force. The former principle gives us the dynamo; the latter, the electric motor.

The figure of the dynamo, Fig. 21, will serve equally well to represent a motor, if we suppose *E* to indicate the source of the current (say a dynamo) which is to be used for driving it. (One slight alteration, however, is necessary in the figure—to this we will refer presently.) Let a current be sent from *E* through the complete circuit, including the magnet coils and the conductor *ab*, in the direction shown by the darts. The magnet will be excited, and a field produced between the poles *NS*. In this field the current passes round the conductor *ab*; which is supposed to be initially at rest. Since, then, we have a conductor lying across a magnetic field and carrying a current, it is clear that a mechanical force will act on the conductor. The tendency in the case illustrated will be for *a* to move down and for *b* to move up; and so the conductor, with its spindle and split ring, will begin to rotate, but in the direction opposite to that shown by the curved arrow. If this is inconvenient in practice, it is only necessary to interchange the wires connected to the brushes *c* and *d* so as to reverse the current in *ab*; this will have the effect of reversing the direction of rotation, so that the curved arrow will then serve as it stands. In order to utilize the power of the motor the spindle *AB* may be connected either directly or by some form of gearing with the machine or apparatus to be rotated. Motors can also be designed to work with alternating currents, but into the principles of these we shall not enter.

III

Radio-activity

Let us consider a single atom of matter, and suppose it to consist of a positive nucleus surrounded by its retinue of negative electrons, the whole constituting a neutral or 'unelectrified' system. Assuming, as we shall eventually have to do, that the atomic constituents are always in a state of violent agitation, it seems possible that some of them might occasionally break away spontaneously from the rest of the atom, and fly off in the form of independent units. This would be more likely to occur in the case of the heavier and more complex atoms, rather than in that of the lighter and simpler ones. Such an effect has, in fact, been observed. Becquerel, in 1896, observed that the heavy metal uranium was capable of fogging a photographic plate although separated from it by an opaque screen. The uranium appeared to give off some kind of rays which could penetrate the screen and act chemically on the plate.

Alpha- and beta-rays. Shortly afterwards Rutherford found the rays to consist of two species; the first, which he called 'alpha-rays', having but small penetrating power—a layer of air about an inch thick being sufficient to stop them altogether. The second species of rays, called 'beta-rays', he found capable of penetrating to a much greater distance in air, and also through considerable thicknesses of solid matter. Both types of rays act on a photographic plate; but the effect is shown in a more striking manner by the beta-rays, on account of their power of passing through much thicker obstacles than the alpha-rays are able to penetrate.

As to the nature of the rays, several possibilities suggest themselves. They might consist of waves, like light or sound. On the other hand, they might be analogous to cathode rays—that is, they might consist of minute charged particles; or, again, we might picture them as particles moving like the cathode rays, but carrying no charge. An obvious method of investigation is to apply electric and magnetic fields to the rays, after the manner adopted in the case of the cathode and positive rays which we have already had occasion to consider. Such fields would tend to deflect the rays if they were composed of charged particles, but not otherwise.

Nature of the rays. Investigations by this and other methods have shown that the beta-rays are identical with the cathode rays; that is, they consist of streams of electrons, carrying their usual negative charges, projected with great velocity from the uranium. The alpha-rays, on the other hand, are found to carry a positive charge, the magnitude of which is twice that of the negative charge of an electron. The mass of one of the particles composing these rays is much greater than that of a beta-particle; it is, in fact, indistinguishable from the mass of an atom of the element helium. The atom of helium is four times as heavy as the atom of hydrogen, but is lighter than any of the other elements. The electron, we already know, is about 1,800 times lighter than the atom of hydrogen.

If we call the charge on the electron an 'elementary negative charge', and a positive charge equal in magnitude to this an 'elementary positive charge' (the latter, by the way, being equal to the charge carried by the hydrogen ion in electrolysis), we may sum up our results by saying that uranium—a 'radio-active' substance—emits streams of particles of two kinds: first, particles four times as heavy as hydrogen atoms, each carrying a double positive elementary charge; and second, particles 1,800 times lighter than hydrogen atoms, each carrying a negative elementary charge.

The velocity with which the beta-particles are projected from the uranium greatly exceeds that of the alpha-particles; this circumstance accounts for the much greater penetrating power of the former, whose velocity, as determined by Becquerel, amounts to about two-thirds of the velocity of light.

Experimental evidence shows that alpha-particles. except for the fact that they have associated with them a charge of electricity, are actually identical with helium atoms; for it is possible to detect the presence (by spectroscopic means) of helium in a closed tube not previously containing any of that element, after it has been permeated by alpha-rays.

Although individual atoms cannot be rendered visible to the eye, it is nevertheless possible actually to see an effect produced by a single alpha-particle—a rather remarkable circumstance. If a small screen, coated with a suitable fluorescent substance, is bombarded at short range by alpha-particles (which can easily be done by bringing a fragment of a radio-active body near to the screen) a distinct flash of light, which can be seen quite clearly in a darkened room, is produced each time a particle strikes the screen.

Let us attempt to visualize the phenomenon of radio-activity in the case of an atom of uranium. First we see, in imagination, the complete atom, with its heavy positive nucleus surrounded by a swarm of electrons, all in a state of violent agitation. On the whole, the atom is electrically neutral, the positive and negative constituents exactly counter-balancing one another. Now a moment of crisis arrives—the atom appears to explode, and a part of it is violently ejected. An alpha-particle has been emitted. The mass of this particle is equal to the mass of 4 hydrogen atoms, or of 7,000 or 8,000 electrons—many more of these than the original atom contained. Moreover, it carries a positive charge equal to the negative charges on two electrons. Clearly, then, the alpha-particle cannot be composed of a group of electrons merely. It must be derived from the heavy positive nucleus of the uranium atom.

Disintegration of atoms. The question arises: What is left of the original atom after the emission of the alpha-particle? In the first place, it is clear that the remnant must be negatively charged to the extent of two elementary charges; for, from the originally neutral system a part, carrying two elementary positive charges, has been removed; the remainder must therefore carry two elementary negative charges, due, presumably, to the existence of two electrons in excess of what it now requires for neutrality. These it will tend to reject, and so become again a neutral system, which we may as well call an atom. The mass of this new atom must be less than that of the original atom. Counting the mass of a hydrogen atom as 1, the mass of the ejected alpha-particle would be 4, and that of the original uranium atom 238. The new atom must have a mass of 234 only. It is radio-active, and emits 2 beta-particles. Whether these are derived from the swarm surrounding the nucleus, or from the nucleus itself—which may contain electrons as well as positive charges—we will leave for future consideration. The atom further ejects successively 2 alpha-particles, the loss of which reduces its mass to 226. It is now an atom of the element radium. Further successive emissions of 5 alpha-particles (as well as some beta-particles which, however, scarcely affect the mass) reduce the mass to 206, leaving an atom which, so far as is known at present, ends the series, and is not itself radio-active. This atom is one of several forms of lead; it is called, in recognition of its parentage, 'uranium lead'. The original atom of uranium has, in fact, been transformed into an atom of lead together with 8 atoms of helium. Other radio-active series also exist, and furnish similar cases of transmutation of elements.

It may be asked: If uranium atoms are continually breaking down into lighter and simpler forms, how is it that any uranium now exists in the world—why has it not long since been reduced to helium and lead? The answer is that in a given quantity of uranium only a very small proportion of the atoms emit rays in such a period as (say) a year or even a century. Many millions of years would elapse before even one-half of the substance would be transformed. Uranium is thus a comparatively stable element. Radium is less stable; half the atoms in a quantity of this substance would disintegrate in about sixteen centuries—not a very long period in the physical history of the earth—but then the supply of radium is being continually replenished by the disintegration of uranium. Several of the elements in the series to which the successive emissions of alpha-rays from uranium give rise have very short lives, some of them being reckoned in minutes or even seconds. These substances are therefore very unstable, and can only be obtained by the disintegration of the elements which come before them in the series; they soon break up into simpler forms, with emission of alpha- or beta-rays. All the lighter elements from lead to hydrogen are stable; though one or two of them emit beta-rays.

Although the rate of transformation of uranium is so slow, it by no means follows that the actual rate at which alpha-particles are emitted by a small portion, such as a gramme, of the substance is small. One gramme of uranium contains many millions of millions of millions of atoms, so that great numbers may disintegrate without making any appreciable difference to the quantity remaining. Radium is more radio-active than uranium, because its atoms emit the particles at a much greater rate; this also accounts for its shorter life. The short-lived substances are still more active; but, clearly they cannot be long preserved. They exist in varying quantities mixed with the parent substance; they continually disintegrate, but fresh supplies of them are continually being formed.

We know that the agitation of the particles of matter is increased by heating, and therefore it might be supposed that emission would be accelerated by heating a radio-active substance. This, however, is not the case. Doubtless the energetic movements in the atom are responsible for the expulsion of the particles; but the amount of energy concerned in such an expulsion is much greater than we could give to the atom by heating; we are unable, therefore, to increase appreciably the rate of radio-emission by this or indeed by any artificial means. The theory of atomic disintegration which we have been considering was enunciated by Rutherford and Soddy in 1903. The discovery of radium, as all the world knows, was due to M. and Mme Curie (1898).

Gamma-rays. A third type of rays, of which brief mention must now be made, is given off by many radio-active substances. These rays, called 'gamma-rays', are capable of acting on photographic plates; but, unlike the other types, they cannot be deflected by electric or magnetic fields; neither do they carry any charge of electricity either positive or negative. They have been found to consist of exceedingly short waves, similar to waves of light, and are therefore fundamentally different from alpha- and beta-rays. They are able to pass through great thicknesses of solid matter opaque to ordinary light—in some cases they have been detected after penetrating a block of iron 12 inches thick. The rays may be supposed to have their origin in the violent disturbances which take place within the atoms during radio-emission.

A source of heat. Another remarkable phenomenon connected with radio-activity, and particularly noticeable in the case of radium, is the continual production of heat which accompanies the process of emission of rays. It is not surprising that a substance in which constant explosions or eruptions are taking place should become heated; but the amount of heat actually generated is surprisingly great. A quantity of radium will give out continuously, every 45 minutes or so, sufficient heat to raise its own weight of water from freezing to boiling-point, and will continue to do so for centuries, without drawing on any external source of energy. This fact gives some idea of the enormous amount of energy stored up (and gradually allowed to escape in the case of radium) in the atoms of the heavier elements. Unfortunately (or perhaps fortunately) we are not able to unlock this energy at will. Could we do so, incalculable powers might be turned to constructive (or destructive) purposes, for the service (or annihilation) of mankind.

Effects of the rays. A radio-active body may be likened to a natural machine-gun, from which a constant succession of projectiles issues with almost incredible muzzle-velocity. True, these are excessively minute; but, we may well ask, are they not likely to be capable of great execution among individual atoms which they may chance to encounter in their way? We know that some of them are able to produce a visible flash on a fluorescent screen; and if we picture an atom, with its complicated planetary structure, we may imagine that the effect upon it of a high velocity alpha- or beta-particle would be very like what we might expect to occur if some heavenly body, detached from its own solar system far away in the skies, were to dash with stupendous velocity into ours. Such a visitor might pass through our system without approaching so near to any member of it as to cause disaster; but, even so, might itself suffer more or less deflection from its straight path on account of the attraction of our sun, or, in a lesser degree, of our planets. But if a direct impact took place both colliding bodies would be raised to incandescence, if not dissipated as vapour. Not quite the same might be expected in the case of the atom; but an electron might easily be detached by the force of the blow.

Consider a quantity of gas enclosed in a vessel into which a fragment of radio-active substance has been introduced. The rays pass through the gas, and in doing so meet in their path many atoms, or those little groups of atoms called molecules, all of which are moving about rapidly in the vessel, and continually colliding with the sides of the vessel and with each other. (This is the picture of a gas presented to us by what is known as the 'kinetic theory of gases'.) It should, however, be remarked that the average velocity of these molecules is—though great—vastly less than that of the alpha- and beta-particles which shoot amongst them. For instance, the molecules of the gases composing the atmosphere move about in all directions (like a swarm of gnats on a summer evening) at an average speed of about a third of a mile a second; whereas the speed of the alpha-particles may be put down roughly at 10,000 miles a second, and that of the beta-particles at more than ten times as much.

Let us follow in imagination an individual alpha-particle in its flight. At first, on leaving the radio-active substance, its velocity is so great that it is not appreciably deflected from a straight line by the atoms through which it passes, unless, perhaps, it happens to approach very near to a heavy nucleus. (We may recall in passing that an alpha-particle is far heavier than the electronic satellites of the atoms among which it moves. Whether it is heavier or not than the atoms themselves—or, what comes to much the same thing, the nuclei of the atoms—depends of course on the kind of gas in the vessel. If this is hydrogen, the alpha-particle is four times as heavy; if oxygen, it is only one-quarter the weight of the atom; while, if the gas is helium, the particle will be identical—except for its speed—with the nucleus of the atom.)

The alpha-particle will, however, detach electrons from many of the atoms it encounters as it pursues its course; and after a time its energy, and consequently its velocity, will be considerably reduced by the constant succession of collisions it undergoes. It may then suffer a great deviation from its original path if it happens to come near to a nucleus. When the velocity is so greatly reduced that the particle is no longer capable of producing drastic effects on atoms, its career as an alpha-ray may be said to be over. It may then gather up a couple of electrons to neutralize its charge, and settle down as an ordinary atom of helium gas.

Ionization. But what of the gas through which it and its fellows have passed? It consists of the unaffected atoms, together with the fragments of the affected ones. Now, these fragments are charged with electricity; for the detached electrons are all negative, and the remnants of the atoms from which they have been dislodged must be positive. The negative electrons may move about, for a time, independently; or they may recombine with positive residues if they happen to meet them, or approach near enough to be attracted to them; or, again, they may chance on neutral or unaffected atoms, and, becoming attached, give them a negative charge. The gas, then, through which the rays are passing or have recently passed contains a proportion of positive and negative particles mixed up with the ordinary atoms or molecules. Gas in this condition is said to be 'ionized'; and the charged particles are called 'ions', a term we have already used in connexion with the electrolysis of liquids.

Now, a gas in this ionized condition acts as a conductor of electricity. Let us suppose two plates, connected to the poles of a battery, to be set up opposite to one another in a closed tube containing the ionized gas. The positive plate will attract the negative ions and repel the positive ones; while the negative plate will attract the positive and repel the negative. Thus two streams of charged particles will be set up in the gas, the positive moving one way and the negative the opposite way. Both streams will conspire to produce a current of electricity, flowing from the positive to the negative plate. The 'current', of course, really consists of two currents flowing in opposite directions, but negative flowing (say) from left to right is equivalent electrically to positive flowing from right to left.

AN ALPHA RAY[1]

Air: 'A Jovial Monk'

An alpha ray was I, contented with my lot;
From Radium C
I was set free,
And outwards I was shot.
My speed I quickly reckoned,
As I flew off through space,
Ten thousand miles per second
Is not a trifling pace!
For an alpha ray
Goes a good long way
In a short time t
As you easily see,
Though I don't know why
My speed 's so high,
Or why I bear a charge $2e$.

And in my wild career, as swiftly on I flew,
A rarefied gas
Wouldn't let me pass,
But I pushed my way right through.
I had some lively tussles
To make it ionize,
But I set the small corpuscles
A-buzzing round like flies.

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[1] By A. A. Robb, from *The Post-prandial Proceedings of the Cavendish Society*. Repeated here by kind permission of the author.

For an alpha ray
Hasn't time to stay
While a trifling mass
Of expanded gas,
That stands in awe
Of Maxwell's law,
Obstructs the road when I want to pass.

An electroscope looked on, as I made that gas conduct;
Beneath the field
The gas did yield
And the leaf was greatly 'bucked'.
But in my exultation
I lost my senses clean,
And I made a scintillation
As I struck a zinc-blend screen.
For an alpha ray
Makes a weird display
With fluorescence green
On a zinc-blend screen,
When the room 's quite dark,
You see a spark
That marks the spot where I have been.

But now I'm settled down, and move about quite slow;
For I, alas,
Am helium gas
Since I got that dreadful blow.
But though I'm feeling sickly,
Still no one now denies,
That I ran that race so quickly
I've won a Nobel Prize.
For an alpha ray
Is a thing to pay,
And a Nobel Prize
One can not despise,
And Rutherford
Has greatly scored,
As all the world now recognize.

Path of an alpha-ray. Reference has been made to an observation of C. T. R. Wilson that condensation of water vapour can be induced to take place on electrified particles. This is effected by suddenly expanding, and so cooling, a volume of damp gas amongst which the particles are distributed. A minute drop of water condenses on each particle; and, if these are sufficiently numerous, the drops can be seen in the form of a cloud. Wilson applied this method to gas contained in a vessel through which alpha-particles were being projected. Suppose the expansion to occur immediately after a particle has passed through the gas, and before the ions caused by its collisions with the atoms along its path have had time to re-combine, or to wander far from the points where they were produced. On each ion a droplet of water condenses, the total result being a fine line of cloud which marks exactly the track of the alpha-particle through the gas. Such a line is actually visible, and can also be photographed. A remark-

FIG. 22. Cloud-tracks of alpha- and beta-rays

able photograph, here reproduced for the first time, through the kindness of Mr. Wilson, shows one of these lines due to an alpha-particle. A sudden bend can be seen, which was caused by the deflection of the particle near the end of its career. When the energy of the particle fell below the amount necessary to produce further ionization in the gas, the visible track came to an end. Beta-rays also ionize gases through which they pass; the photograph shows the track of one of these which happened to pass at the same time as the alpha-ray. It appears in the form of a faint curly knotted line near the middle of the plate, just below the alpha-track.

The charge on an electron. The ionization of air was also utilized in a remarkable manner by R. A. Millikan, of Chicago, in carrying out experiments by which he was able to measure the charge carried by a single electron. Millikan fixed two horizontal metal plates, one above the other, and charged them—one positively and the other negatively. Through a small hole in the upper plate he allowed very minute droplets of oil to fall, from a chamber above into which a quantity of oil had been sprayed. By means of a microscope and powerful illumination it was possible to trace the descent of the drops through the layer of air existing between the plates, and to measure their velocity as they fell. (This velocity is not great in the case of minute drops falling through air.) When all was in order, Millikan ionized the air between the plates by passing through it a beam of suitable rays; and so produced in the space through which the drops were descending a plentiful sprinkling of positive and negative ions. Now, these ions, like the air particles which were unaffected by the rays, moved rapidly about the space, and occasionally struck the drops of oil (which, though small, were immensely greater than the ions) and became attached to them, thus giving the drops a charge, positive or negative as the case might be, of electricity.

Suppose a single electron adheres to a given drop; the charge on the drop will obviously be what we have called an elementary negative charge. If two electrons adhere, the charge will have twice this value; and so on. No fractional charge is possible; in every case the charge on the drop must be exactly equal to one, or to some definite whole number of elementary charges. The same is true if the drop receives one or more positive ions. In other words, every drop which receives a charge at all must receive either one elementary charge, or some multiple of that amount.

Now, suppose an experiment to be in progress. The observer, watching through the microscope, notices a drop descending steadily from the hole in the upper plate towards the lower plate. The drop, we will suppose, is at first uncharged; but, suddenly, an electron, which has been detached from an air particle by the ionizing rays, happens to become attached to it. We have now a negatively charged body (the drop) in a space between two charged plates—the upper of which we will suppose to be positive, and the lower negative. While the drop remained uncharged, the plates did not affect its motion; but now the upper plate attracts and the lower plate repels it. The result is that the drop is urged upwards by the electric forces; and while these may not be sufficient to counteract entirely the downward motion due to the weight of the drop, they do actually retard the downward velocity to an extent which can be observed, and measured by means of microscope and stop-watch. Thus, when the drop is uncharged, it travels steadily down in the field of view of the microscope; but the instant the electron becomes attached to it this downward velocity is partially checked. Millikan was able, after measuring this retardation, to calculate with great exactness the actual magnitude of the charge on the drop. This charge was not of course always that of a single electron (it was often a multiple of that charge) but fractional charges were never obtained; so that, after a number of observations, it was possible to find out exactly what the unit or elementary charge actually was. This measurement must rank as one of the most extraordinary that has ever been made.

IV

Atomic Architecture

THE modern science of atom building has hardly emerged as yet from the embryonic stage. It is highly mathematical, and in some respects not very susceptible of physical representation. It is, however, of fundamental importance to our subject; and, by confining ourselves to general descriptive methods, we may be able to avoid unnecessary complication and obtain a knowledge, sufficient for our purpose, of this interesting branch of research.

Constitution of the atom. Something of the constitution of the atom we have, indeed, already learned. Beginning with the simple conception of Rutherford, we imagine the atom as a small positive nucleus with one or more negative electrons revolving around it. A study of radio-activity has shown us that the heavier atoms are capable of spontaneously emitting particles (alpha-particles) which prove to be identical with positively charged atoms of helium. These particles are four times as heavy as hydrogen atoms; and they carry a positive charge equal to twice the negative charge on an electron. They are derived from the nucleus of the emitting atom. The beta-particles, which are also emitted by the radio-active atom, are ordinary negatively charged electrons. In our previous discussion of the subject we left over the question as to the origin of these particles. Since the emitting atom has a swarm of electrons round its nucleus, we might suppose some of these to be given off as beta-particles; but the violent nature of the ejection of both alpha- and beta-particles leads us to suspect that they both come from the same source—the nucleus—which we may regard as a kind of centre of volcanic activity. This supposition necessitates the conclusion that the nucleus of the heavy atom contains electrons as well as positive charges. In this case, the net positive charge of the nucleus must be due to a preponderance of positive over negative; and this net positive charge must be neutralized in the complete atom by the electrons which revolve around the nucleus. The complete atom must therefore contain both 'nuclear' and 'extra-nuclear' electrons, as well as positive 'nuclear' charges. (Suppose, for example, that a certain atom comprises in its nucleus 23 elementary positive charges together with 12 electrons; the number of extra-nuclear electrons must be 11.)

We know, also, that most of the mass of an atom resides in its nucleus; for the electrons are very light, and unless we suppose them to be present in enormous numbers they cannot contribute much to the mass. This is equally true of the electrons within and without the nucleus, so we must conclude that the mass is principally due to the positive charges in the nucleus.

The proton. Let us now consider the simplest known atom: the atom of hydrogen (which, of course, is not radio-active). We assume it to be made up of a simple positive nucleus—whose mass, which we will reckon as unity, is practically that of the complete atom—and an electron of negligible mass revolving about it in an orbit. The nucleus we suppose to carry an elementary positive charge, and the electron an elementary negative charge, the atom as a whole thus being neutral. The nucleus of hydrogen, on this view, contains no electrons; it is purely positive. The name 'proton' has been assigned to it by Rutherford. The hydrogen atom, then, consists of a nucleus of one proton together with one extra-nuclear electron.

The helium nucleus. Next, let us attempt to build up the atom which comes next to hydrogen in order of simplicity; the atom of helium. Assuming it to be composed of protons and electrons—though whether the protons remain discrete bodies, or coalesce to form larger positive aggregates we need not discriminate—we can at once specify the number of protons in the nucleus, for the mass of the atom is four times that of the hydrogen atom; it must therefore contain 4 protons. Since it is neutral, it must also have, in all, 4 electrons. We know, moreover, that an alpha-particle is identical with a helium atom having 2 elementary positive charges, and that this is ejected from the nucleus of a heavy radio-active atom. The latter fact leads us to suspect that the alpha-particle is simply the nucleus of a helium atom—that is, a helium atom without any extra-nuclear electrons. But the charge on an alpha-particle is 2, while the helium nucleus contains 4 protons, whose positive charge is 4. We must conclude, therefore, that the helium nucleus contains 2 electrons in addition to the 4 protons, making the positive nuclear charge 2, and leaving 2 electrons for the extra-nuclear structure of the complete atom.

We may arrange our conclusions in tabular form thus:

TABLE I

	Nuclear Structure			Extra-nuclear Structure	
Name of atom	Number of Protons	Number of Electrons	Net charge on Nucleus (positive)	Number of Electrons	Charge on Ex.-nuc. Str. (negative)
HYDROGEN	1	0	1	1	1
HELIUM	4	2	2	2	2

To visualize, roughly, the atoms—but without in any way committing ourselves as to the actual arrangement of their different constituents—we may plot them out in the following way; adding for comparison the alpha-particle, and the beta-particle or electron:

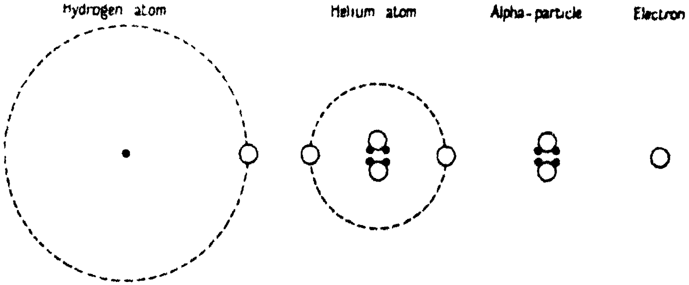

FIG. 23. To illustrate atomic structure

In these diagrams the black dots represent protons; the small circles electrons; and the dotted circles the orbits of the extra-nuclear electrons. The diagrams are not drawn to scale, though the orbits of the two atoms represented are shown approximately in their correct proportions. The protons, though much heavier than the electrons, are shown smaller; their great mass being closely associated with the high concentration of their charges. The picture here given of the helium nucleus is not intended to represent in any way the arrangement of the parts of which it is composed, but simply indicates that the positive part of it is equal to 4 protons, and that with this positive part are associated 2 negative electrons. The outer electrons of helium are shown on a single orbit, but in actual fact each has probably a separate orbit of its own. With these details, however, we need not concern ourselves.

Size of the atoms. As to the size of the atoms, very little can be conveyed by the mere quotation of figures. Suppose, however, that small rings or pellets, equal in diameter to the orbits of the hydrogen atoms, could be laid side by side, touching one another, so as to cover the surface of a postage stamp; and suppose them to be placed in position at the rate of 5 per second—that is, one for each tick of a watch. Some idea of their minuteness may be gained from the fact that 300 million years would be required in which to cover the proposed area.

If the orbit of the hydrogen atom were magnified to the size of the equator of the earth, the proton at the centre would have a diameter of about 5 inches; and the diameter of the electron revolving round the equator would be about 800 feet. All the rest would be empty space. Or, on the magnified scale, the hydrogen atom would consist of a heavy mass 5 inches diameter with a light body 800 feet diameter revolving round it at a distance of 4,000 miles.

We can form a rough estimate of the total number of protons in the earth, if we assume all the mass of the earth to be due to the protons. For the mass of the earth is about 5×10^{27} grammes (which means 5 with 27 0s following) while the mass of one proton is about $165 \div 10^{26}$ (i. e. 165 divided by 1 with 26 0s). If we now divide the earth's mass by the mass of one proton, we obtain the number of protons; about 3×10^{51}. Further, on multiplying this number by the volume of one proton (assumed to be a sphere of radius $1 \div 10^{16}$ centimetres), we arrive at the total volume of all the protons in the earth supposed concentrated into one body. This, if shaped into a ball, turns out to be rather less than one foot in diameter. With the exception of the small fraction of the mass contributed by the electrons, we thus see that the massive part of the whole earth could, if it were possible to eliminate intervening spaces, be packed into a moderate sized hand-bag. The electrons would bulk much larger; but even they would not fill a sphere half a mile in diameter. Similarly, the constituents of the body of a fully grown man would find room to spare in a sphere one-thousandth of an inch in diameter. So you, my dear reader, vacuities apart, are of no more than microscopic dimensions!

The heavy atoms. Let us now turn our attention to the heavy atoms—those comprising heavy nuclei and large numbers of electrons. Consider the atom of uranium, which is the heaviest known. Its mass is 238 times that of the hydrogen atom; that is, its nucleus contains positive electricity equal to that of 238 protons. For simplicity, we will say that it contains 238 protons. But the nucleus also contains electrons. We are not in a position at the present stage of our inquiry to say how many, but we can derive some information on this point if we consider the radio-active emission of alpha- and beta-particles by the uranium. We have already seen that, in becoming transformed into radium, the uranium nucleus emits 3 alpha-particles and 2 beta-particles. Since each alpha-particle comprises 4 protons and 2 electrons, and each beta-particle is an electron, it follows that the total emission of the uranium nucleus in its transformation to radium is equal to 12 protons and 8 electrons. The loss of 12 protons means that the radium atom must be 12 units lighter than the uranium; this gives 226 as the mass of radium, which is correct. Also, whatever number of electrons the radium nucleus contains, the uranium nucleus must contain 8 more. Going a stage farther in the radio-active process, we find that the radium nucleus emits 5 alpha- and 4 beta-particles during its transformation to lead. Thus lead contains 20 protons and 14 electrons less than radium. The mass of the atom of lead should thus be 20 units less than that of radium, or 206; and its nucleus should contain 14 less electrons than the nucleus of radium, and therefore 22 less than that of uranium.

Since lead is not radio-active we cannot pursue our investigation any farther along these lines. Could we do so, we should be able to determine the number of electrons in the nucleus of lead, and of the other elements; but we cannot bridge the gap between lead and helium. We have just seen that the mass of the atom of lead (or the atomic weight as it is generally called) is, according to our calculation, 206. A fear strikes me that the reader may refer to a table of atomic weights and find a discrepancy; so perhaps I had better not attempt to conceal the fact that the atomic weight of lead is not 206, but 207·2. However, let us have the courage of our convictions, and, after setting out our results to date in tabular form, carry on our inquiry in another direction.

In the table x represents the unknown number of electrons in the nucleus of lead. The last two columns added together give the total number of electrons in the complete neutral atom, which is equal to the number of protons given in the first column of figures.

TABLE II

Name of atom	No. of protons in nucleus; which is also equal to the atomic weight	No. of electrons in nucleus	No. of extra-nuclear electrons; which is also equal to the net charge on nucleus
HYDROGEN . .	1	0	1
HELIUM . .	4	2	2
LEAD . . .	206	x	$206-x$
RADIUM . .	226	$x+14$	$212-x$
URANIUM . .	238	$x+22$	$216-x$

The ether of space. Since we cannot carry out our investigations on radio-activity below lead, and so determine the unknown value of x, let us now turn our attention more particularly to the outer or extra-nuclear electrons of the atom. But first let us introduce the notion of the ether of space. This is an all-pervading medium which fills not only interstellar space, but also the spaces between atoms, and the spaces in the atoms themselves between the electrons and protons therein contained. True, the modern doctrine of *Relativity*[1] has rudely shaken our views of the ether; and we may have to look on the picture we are about to draw rather as an analogy than a definite representation of fact. But we must have some kind of mental representation; unless, indeed, we are content to work with mathematical symbols—as the modern theorist is, in fact, rather inclined to do.

Electro-magnetic waves. The electrons, then, swirl about in a sea of ether. Take a large basin of water, and dip into it the end of a pencil. Move this as rapidly as you can backwards and forwards over a short range, say an inch, or round and round in a little circle. You will find that a series of waves or ripples will start from the centre of disturbance, and move quickly across the surface of the water. The water represents the ether, and the pencil a moving electron. No doubt the picture is crude, and does not in all respects represent the most modern theory of the origin of waves; but it will serve us well enough for the present. The waves given off by the electrons are called 'electro-magnetic waves'; they are not exactly like the water ripples—which are called into play by mechanical forces—but are rather due to the electric and magnetic forces called into play by the electrons and their motions. Nevertheless, the two kinds of waves have many properties in common. Move the pencil rapidly backwards and forwards, and you will find that the resulting wave crests will be close together; move it more slowly, and the crests will be farther apart. The distance from crest to crest is called the 'wave-length', and the number of oscillations of the pencil per second the 'frequency'. This simple experiment shows that the greater the frequency, the less the wave-length; and vice versa.

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[1] *An Outline of Relativity* (Epworth Press), by the present writer, may be consulted on this subject.

Suppose we have in an atom a number of oscillations of different frequencies, due to different electronic motions (of types which we will not particularize, in view of the theory to be mentioned later); we may expect that waves of different wave-lengths will be emitted by the atom. The greater the agitation of the atom, due (say) to heat or other causes, the greater will be the intensity (and possibly also the variety) of the waves emitted.

Is there any evidence of the emission of such waves? Heat a piece of wire, say the filament of an electric lamp, by the passage of a current of electricity. What follows? Light is emitted.

Maxwell's theory of light. Now, as far back as 1873—long before electrons were discovered—Clerk-Maxwell (1831–79) had founded his electro-magnetic theory of light. Light, he concluded, consisted of just such waves as those we are now considering. The science of light thus takes its place as a branch of electro-magnetics. Since light waves are emitted by atoms of matter, it is clear that a study of these waves, emitted under different conditions and by different kinds of atoms, may be expected to yield information as to the constitution of the atoms themselves. Apart from this, the study is important in itself; and we must now, for a short time, turn our attention towards it.

The spectrum. A beam of white light is highly complex, and it is common knowledge that by means of a triangular prism of glass it can be split up, as was first shown by Newton, into all the colours of the rainbow. The succession of colours thus produced is called a ‘ spectrum ’. Spectra differing widely in appearance are produced if different sources of light, white or coloured, are used. We need only concern ourselves with two kinds: continuous spectra, and line spectra. The former consist of continuous bands of colour, varying from red at one end to violet at the other. They are produced by the light of incandescent solids, luminous coal-gas flames, &c. The line spectra consist of thin discrete lines of light of different colours; and so far as appearances go could be obtained by taking a continuous spectrum and blacking out all except a number of thin strips of various colours—these strips being perpendicular to the length of the spectrum. Every line has therefore a definite colour corresponding to its position in the spectrum, and is due to light of a particular wave-length. In the continuous spectrum all wave-lengths between those corresponding to the red and violet limits are represented; in the line spectra certain isolated wave-lengths alone exist.

The line spectra are produced by luminous gases and vapours; they can be obtained by holding various salts in the flame of a bunsen burner, or by passing an electric discharge through a rarefied gas in a 'vacuum' tube. Different gases and vapours give different spectra; that is, they emit light containing different selections of wave-lengths, no two of the spectra being alike. It is by the study of these wave-lengths that we may expect to derive information about the motions of the electrons in the atoms which produce them. We shall not be able to pursue such a study in detail; but a little consideration of the subject of wave-lengths will repay our attention.

Instead of the glass prism another piece of apparatus, known as the diffraction grating, is often used for producing spectra; and also for measuring the wave-length of the light corresponding to any line in a line spectrum. Take an analogy. Imagine a column of men marching towards a wall *AB* pierced by a set of openings, each sufficient for a man to pass through. Let each man, without pausing or altering his pace, change his direction as shown in the figure the moment he passes through one of the openings in the wall. At a given instant let the attention be fixed on the men who, at that instant, occupy the positions marked 1 to 6 on the diagram. Now, when the whole column has moved forward 5 places, it is clear that these men will have reached the positions marked by crosses along the line *EB*. These men will subsequently march exactly abreast, and will, of course, be in step with one another. Similarly with all the other men; we shall, in fact, have a new regular formation along the new line of advance. But, for this to occur, the new direction must be correctly chosen—chosen, that is, so that the distance *AE* will equal exactly 5 places.

Now suppose the column to represent a beam of light of one particular wave-length, and let successive waves be represented by the rows of men marching abreast; as *CD*, *FG*, and so on—the distance between two rows corresponding to one wave-length. Let the openings in the wall represent small apertures in an opaque plate, so that only small bits of each wave can get through. Each bit, after passing through its aperture, would spread like a circular water ripple; but on account of the presence of the others we could only expect a regular wave to form beyond the row of apertures if all the bits of the beam which pass through fall into regular formation like the column of men. This they will do along the direction of the line *AE*; and all we have said about the men will apply to the waves. In the figure the distance *AE* must equal 5 wave-lengths; and for this to occur the direction of *AE* must be correct. Evidently, if we know the wave-length we can

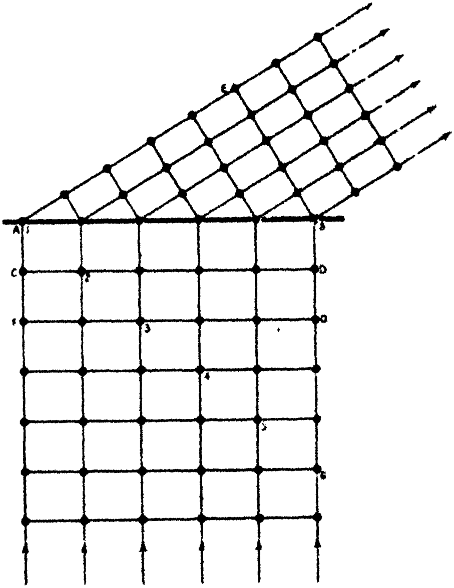

FIG. 24. To illustrate the diffraction grating

determine the direction *AE* of the new wave; or, if we actually try the experiment, and observe this direction, we can determine the wave-length of the light.

Invisible regions of the spectrum. Experiments on these lines show that red light has about 33,000 waves to the inch, and violet light about 70,000 to the inch. Between these limits lie the waves corresponding to all the other colours of the spectrum. It is possible, however, to detect waves which lie outside these limits. The complete spectrum (of, say, an electric arc light) is not really confined to the visible region we have been considering. Beyond the red, in what is called the 'infra-red' region, lie waves which are too long to excite vision; but they are in other respects similar to those of the visible spectrum. They can be detected by their heating power; they are of the type given off by a poker heated to a point somewhat below red heat. A red-hot poker gives off, in addition to infra-red rays, a certain quantity of waves belonging to the red end of the visible spectrum. Beyond the violet, in the part of the spectrum known as the 'ultra-violet', are ranged waves too short to excite vision. These can be detected by their action on a photographic plate, which they affect in the same way as ordinary light. In addition to the waves in the visible and invisible parts of such spectra as we have been studying, others—both longer and shorter—can be excited by suitable means. These we shall subsequently examine; but we must now return to the consideration of the outer electrons of the atoms which, by their motions, are responsible for the production of the waves in the various parts of the spectrum.

Bohr's theory. Is it possible to form any distinct idea of the motions of these electrons while they are emitting light waves? A theory, founded in 1913 by Bohr of Copenhagen, has proved, on the mathematical side, eminently successful in the case of the simpler atoms, and not a little fruitful even in the more complicated cases. This theory is an extension or elaboration of Rutherford's. Taking the simplest atom—that of hydrogen—Bohr supposes that the single electron is capable of revolving around the central nucleus in any one of a number of different orbits of certain specified diameters, but that it cannot revolve in any intermediate orbits. We may picture the possible orbits as rings of different sizes round the nucleus, like the rings on a target round the bull's-eye.[1] While moving in one of these orbits the electron does not produce waves in the surrounding space. But, under certain circumstances, the electron suddenly jumps from an outer orbit to an inner one; and in doing so it emits (according to the theory) a series of waves having a frequency which depends on the particular orbits concerned.

To make an electron pass from an inner to an outer orbit it is necessary to supply it with energy (by heating, say), and on jumping back again the electron gives out this energy in the form of waves. How can we picture these rather peculiar processes? Unfortunately the modern theories tend to be mathematical, and do not always lend themselves very easily to mental visualization. Perhaps a crude illustration may help. Suppose we have a motor which is capable of running at certain definite speeds, say 100, 200, 300, revolutions per minute, but not at intermediate speeds. At any of these speeds it runs quietly and smoothly, but on changing over from one speed to another a jolting occurs which occasions much noise or emission of sound waves. With the new speed quietness again obtains. Something of the kind seems to occur in the atom. While the electron is moving in any of its possible orbits a certain tranquillity prevails; this is disturbed if the electron changes over to an inner orbit, with the result that waves are generated. Then the atom settles down again to the new conditions, and the production of waves ceases.

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[1] Actually the orbits are more complicated than this. They are not all circular, and they do not all lie in the same plane.

The theory is intimately connected with the 'quantum theory' which was founded in 1900 by Planck of Berlin, and according to which the atom cannot give off energy continuously, or in a gradual and uniform manner; but only in certain specified amounts or 'quanta'. If, therefore, energy is to be radiated from the atom in the form of waves it must be given off in quanta; one, two, three, or more, as the case may be—fractional parts of a quantum being inadmissible. The evolution of energy is thus spasmodic; and it occurs, as we have seen, according to Bohr's theory, when the electron suddenly passes from an outer orbit to an inner one. Let us number the possible orbits 1, 2, 3, and so on, beginning with the innermost. Then (leaving out of account certain elliptical orbits, the consideration of which would lead to unnecessary complication) whenever an electron jumps from any orbit to the one next below it in number—say from 6 to 5, or from 5 to 4, a quantum of energy is given off,[1] if it jumps from (say) 6 to 4, or from 5 to 3—a jump of two orbits—a larger quantum is given off, and so forth. It is evident that many different jumps are possible; and these different jumps give rise to the emission of waves of different frequencies. This affords an explanation of the fact that hydrogen (say) is capable of giving out light of a number of different, yet quite definite frequencies.

In the spectrum of hydrogen, produced by passing a discharge of electricity through a hydrogen vacuum tube, and resolving the emitted light by a prism or grating, several bright lines are easily observed. One of these, a red line, is produced by a jump from orbit 3 to orbit 2; and another, a blue line, by a jump from 4 to 2.

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[1] These quanta are not all equal. Their magnitudes are proportional to the frequencies of the emitted waves, but this complication need not trouble us.

Other lines, both in the visible and invisible parts of the spectrum, are satisfactorily accounted for in a similar way. We must suppose that the passage of the discharge through the rarefied hydrogen in the vacuum tube shakes, as it were, many of the electrons belonging to the different atoms into orbits considerably removed from the nuclei, thereby imparting energy to them. This energy is given out again in the form of waves as the electrons jump back to orbits nearer the nuclei; some jumping in such a way as to produce the red line, some the blue, and so forth.

Obviously a much more complicated state of things must exist in the case of the heavy atoms with many electrons. Considerable progress has, however, been made with the theory on principles similar to those which apply to hydrogen. In these cases numbers of electrons revolve about the nucleus at varying distances from it. Again, only definite orbits are possible; and when the electrons pass from one to another they either take in or give out energy in a manner similar to what we have described in the case of hydrogen. It is most convenient to think of the electrons as ordinarily arranged on several rings; these rings, of course, representing a series of the 'possible orbits'. In such a case the electrons on the inner rings are not so susceptible to disturbances from outside as those on the outermost of the occupied rings. It is, therefore, the outer electrons that are chiefly concerned in the production of light waves, when, after being jerked to still more remote orbits, they jump back again towards their ordinary positions. Sodium vapour (atomic weight, 23) when heated to incandescence gives out an intense yellow light; in the emission of this the outer electrons of the atoms are concerned. Many of the elements give rise to vast numbers of lines in their spectra, indicating a complexity quite beyond the powers of any theory, in the present state of science at least, to explain.

Bombardment of the atoms. We have just said that the electrons on the inner rings—that is, the rings nearest the nuclei of the heavier atoms—are not very easily disturbed by outside influences. But an exception must be made to this statement. Suppose one of the heavier atoms to be bombarded by cathode rays, which we know consist of rapidly moving electrons. These can penetrate the spaces between the electrons of the atom, and may, by collision, displace some of them ; the inner ones cannot escape such disturbances, and may therefore be set jumping—just as the outer ones are, when subjected to the less drastic influences of ordinary heating. The theory shows that, under these circumstances, when one of the inner electrons jumps back to its ordinary orbit after being thus displaced to one more remote, waves of extremely short wave-length should be emitted. Such waves are far too short to be represented, like those due to the outer electrons, on the ordinary spectrum.

X-rays. Now, as long ago as 1895, the German physicist Röntgen, while experimenting with cathode rays, which he was generating in a tube enclosed in an opaque cover, found that a fluorescent screen some distance away glowed brightly whenever the cathode rays were produced. This effect he traced to a new type of rays which were capable of penetrating substances opaque to ordinary light and acting on fluorescent bodies in the manner observed. They were also found to act on photographic plates, ordinary coverings affording these little or no protection. The rays, called by Röntgen ‘ X-rays ’, differed from ordinary light not only in their extraordinary penetrating powers, but also in that they could not be reflected by a mirror nor concentrated to a focus by a lens. It was soon shown that the rays proceeded from the parts of the discharge tubes which were struck by the electrons constituting the cathode rays. For some time the nature of the rays was a subject of controversy; but they were eventually shown to be electro-magnetic waves similar to the waves of ordinary light—the peculiarities in their properties being accounted for by the extreme shortness of their wave-lengths.

Here then, ready to hand, we have experimental evidence of the existence of short waves due to the bombardment of the atoms of matter by cathode rays. In this connexion some remarkable experiments were made by Moseley, a young English physicist, whose life was sacrificed in the trenches in 1915. Moseley bombarded with cathode rays a number of different substances, comprising many of the chemical elements obtainable in the solid form, and analysed the X-rays which were thereby generated. In doing so he made use of a discovery of Laue, of Munich, who found that crystalline substances, on account of the regular spacing of their molecules, could be made to act as natural diffraction gratings for the detection and measurement of extremely short waves like those of the X-rays—ordinary manufactured gratings being much too coarse for this purpose. The method of Laue was modified and improved by W. H. and W. L. Bragg, and adapted by Moseley to his experimental requirements.

The results proved to be of great importance in atomic theory; for he found that when the cathode rays were made to impinge on the various atoms ranged in the order of their atomic weights, the wave-lengths of the resulting X-rays varied from atom to atom in an almost perfectly regular manner—the heavier the atom the shorter the wave-length generated. A few slight exceptions to this rule were discovered; but, whereas the atomic weights vary from atom to atom in a very irregular way, the wave-lengths vary in an extremely regular way; and therefore the classification of the elements by reference to these wave-lengths is preferable to the older classification which depended on the atomic weights.

Another interesting feature of the results was that several atoms were clearly missing from the series; for, in a few cases, the change in the wave-length obtained by passing from one atom to the next of the known series of atoms was exactly what it should have been in passing to the next but one—that is to say, an atom was evidently missing from the known series.

Atomic numbers. The number of any atom in the series thus determined is called its 'atomic number'. The missing atoms have their appropriate numbers allotted to them, and may be discovered some day. The numbers range from 1, for hydrogen, to 92, for uranium—the heaviest known atom; for, though the method of experiment does not apply to hydrogen and a few of the other elements, there can be no doubt as to the positions of these in the series. On the basis of these results we are justified in concluding that not more than 92 separate elements exist in nature, unless (which is hardly likely) there should be some with higher atomic numbers than that of uranium.

A consideration of Moseley's results will enable us to complete our study of atomic nuclei which was interrupted by our inability to determine the number of electrons in the nucleus of the atom of lead—a number we represented in Table II, by the letter x. The X-rays produced in Moseley's experiments are due to those 'extra-nuclear' electrons which circulate about the nuclei in the smaller orbits. Their motions are powerfully affected by the nuclei, and it is not unreasonable to suppose, as, in fact, the theory indicates, that the wave-lengths of the rays emanating from these electrons will depend upon the nuclei—or rather, on the nuclear charges—of the atoms concerned. Since the wave-lengths vary regularly with the atomic numbers of the atoms, we may conclude that the nuclear charges also vary regularly with the atomic numbers.

Constitution of the nucleus. Let us see whether we can fit any data to this idea. In the first place, we know—in accordance with the last column of Table II—that the nuclear charge of hydrogen is 1 and that of helium 2, while the atomic numbers of these elements are also 1 and 2 respectively. Again, we see in the same column that the net nuclear charge of uranium exceeds that of radium by 4 protons, and that of lead by 10 protons. How do these numbers fit in with our hypothesis? The atomic number of lead, according to Moseley's experiments, proves to be 82. If this is equal to the nuclear charge of lead, expressed in protons, then the atomic number of uranium—with 10 more protons—should be 92; and that of radium—with 4 protons less than uranium—should be 88. These numbers are correct; and we therefore conclude that the atomic number of any element represents the nuclear charge of its atom expressed in protons. The value of x, therefore, on the table, can easily be determined; for in the case of lead we have, in the last column, the value $206-x$ for the nuclear charge; this we now know to be equal to 82, the atomic number; therefore the value of x must be 124. The value 124 could now be filled in for the other elements on the table, and the specification completed for all the 92 atoms—even including the missing members of the series. The last column of the table would simply be a list of the numbers from 1 to 92, and would represent both the nuclear charges and atomic numbers of the successive elements.

We have now only one difficulty to clear up in our elementary survey of the constitution of the atoms. According to our theories, the atomic weight of lead appears to be 206; whereas the value given in tables of atomic weights is 207·2. The discrepancy is really twofold; for not only do these values differ considerably from one another, but the latter is not a whole number. Now, if our theory is correct in that the atomic weight is equal to the total number of protons in the atom, and the protons are indivisible, it is clearly impossible for the atomic weight of any atom to be 207·2, for this would require 207·2 protons, 'which is absurd.'

Isotopes. In this connexion we must refer briefly to some observations of fundamental importance by Aston, of the Cavendish Laboratory, Cambridge. We saw in Section I that, by the method of positive rays, it was possible to ascertain the masses of the atoms contained in the tube in which the rays were generated. Now, Aston, by means of an improved apparatus, succeeded in determining with great accuracy the masses of different kinds of atoms which he introduced into his tubes. A glaring instance of fractional atomic weights is that of the gas chlorine, whose atomic weight is given as 35·5. Using this gas, Aston found atoms of mass 35 and others of mass 37, but none of mass 35·5. The two kinds of atoms were mixed in such proportion as to give an average mass of the ordinary value, 35·5. The element chlorine was thus shown to consist of a mixture of two kinds of atoms, each having a whole number mass. The two kinds are chemically identical; the mixture is not like a mixture of (say) oxygen and nitrogen—gases which form the chief constituents of atmospheric air—but is simply a mixture of two kinds of chlorine, which cannot be distinguished or separated from one another by chemical methods. Similar conclusions had also been reached with respect to the radio-active elements and lead. The different species of atoms of an element which have different atomic weights are called 'isotopes'.

In ordinary chemical reactions and in such processes as heating, the nuclei of atoms undergo no dislocation; the extra-nuclear electrons only are involved. Since the number of these depends on the nuclear charge of the atom, it is clear that if we have two atoms in which the nuclear charges are equal, the two atoms will be chemically identical—even though the total number of protons they contain (which number determines their atomic weights) may differ. Thus, in the case of chlorine, whose atomic number (and nuclear charge) is 17, we may have an atom with 35 protons and 18 electrons in its nucleus—giving the required charge of 17, with atomic weight 35; and another atom with 37 protons and 20 electrons giving also a charge of 17, but an atomic weight of 37. Many other instances of isotopes have also been found, among these being isotopes of lead of atomic weights 206, 208, &c. The first of these has the value our deductions required; and the value for ordinary lead is accounted for on the supposition that it is composed of a mixture of different isotopes.

In following out radio-active changes it is convenient to note that the emission of an alpha-particle reduces the net positive charge on the nucleus by 2, while the loss of a beta-particle increases it by 1. For example, the uranium atom, after emitting 1 alpha- and 2 beta-particles, has the same nuclear charge as before (though its atomic weight has been reduced from 238 to 234); it has therefore become an isotope of uranium.

We may at this point bring our investigations on the structure of the atom to a close.

V

Electro-magnetic Waves

We have formed a conception of matter as an openwork structure of extraordinary complexity, all the parts of which are subject to constant and violent agitation. But, even so, the normal condition of matter seems comparatively tranquil when we consider the dislocations caused by the eruption of particles, which sometimes occurs, from the inner recesses of the atoms. These varied agitations and disturbances we know to be the origin of waves which penetrate matter itself and emerge into the surrounding space. The waves, though all of the same general type, differ enormously in size or wave-length, and consequently in their effects on the various kinds of matter which they may encounter. Since different kinds of matter vary greatly in structure—we have knowledge not only of nearly all the 92 elements, but also of innumerable combinations of these—it is not difficult to realize that the effects upon them of the various waves will be diversified in the extreme; and that the waves will play many and important parts in the pageant of nature.

Wave-lengths. It often happens when we deal with natural magnitudes that a mere quotation of figures conveys very little idea of their real dimensions. This is so in the case of the waves now under consideration. The wave-length of the shortest gamma-rays of which we have knowledge is about one twenty-five thousand millionth of an inch, and that of the longest infra-red about one-eightieth of an inch. Let us, for the sake of comparison, magnify the waves to such an extent that the shortest becomes equal in length to the thickness of a sheet of average paper—300 sheets to the inch—which will necessitate a multiplication of about 83,000,000—then the longest infra-red will correspond to about 16 miles. On the same scale, the waves which excite vision will range from 100 feet to a little over 200 feet; the X-rays, and, partially overlapping them, the ultra-violet from about one-twentieth of an inch to the length of the shortest visual waves. The gamma-rays also to some extent overlap the X-rays, and vary from the thickness of the paper to about half an inch.

The shortest waves—those constituting the gamma-rays—have their origin in the nuclei of several of the atoms which exhibit radio-activity. They are the most penetrating of all the waves. The X-rays proceed from the inner rings of electrons which surround the nuclei, and are induced by the impact of cathode particles which enter the atoms from without. These rays are highly penetrating; but less so, on the average, than the gamma-rays. The gamma- and X-rays form a continuous series; they are only known by different names because they are differently produced. The overlapping of the X-rays and ultra-violet also indicates afresh that there are no differences, except in length, among the various waves of the series.

The waves capable of exciting vision form a very small proportion of the whole range. These, with the waves belonging to the ultra-violet and infra-red portions of the spectrum, are emitted by the outer electrons of the atoms. Their penetrating power is much less than that of the X-rays; and for particular substances, the shorter waves are not always more penetrating than the longer ones. The shortest ultra-violet rays are stopped by glass, which the longer visual rays penetrate with ease. Red glass is transparent to the longer rays of the visible spectrum—those which excite the sensation of red—but opaque to the shorter rays which give rise to the sensation of blue. Blue glass, on the other hand, is penetrated by 'blue rays' but is opaque to red. The general explanation of this is, that the atoms of different substances respond differently to different waves; when an atom is thrown into vibration by a particular wave it absorbs that wave, but allows others to pass unimpaired. An important property of all the waves, from the gamma- to the visual rays, is their power of affecting the photographic plate. The longer waves, in the infra-red, are notable for the heating effect they produce in bodies on which they fall; a property which is shared to a certain extent by the shorter waves, particularly in the visible part of the spectrum.

Let us now turn our attention to some of the more important applications of the different categories of the electro-magnetic waves whose general properties we have been considering. The *gamma-rays* need not detain us. Their origin and remarkable penetrating powers have already been discussed. The longer waves of this type are identical with the shorter of the X-rays; and we may pass on at once to a consideration of the latter.

X-rays

Production of X-rays. X-rays are emitted when matter is bombarded by cathode rays. In an ordinary discharge tube, such as we have already described, the cathode rays proceed in straight lines from the surface of the cathode; and it is possible, by using a curved cathode, to concentrate them on to a small metal plate or 'target', which then evolves the X-rays in abundance. Although a tube of this kind must be highly exhausted of air, the exhaustion must not be carried to an extreme; for a small quantity of air or other gas is necessary to enable the rather complicated process, on which the emission of the cathode rays depends, to take place. In the 'Coolidge' tube, Fig. 25, now largely used, a different principle is employed for the production of the cathode rays—a principle which, applied in another way,

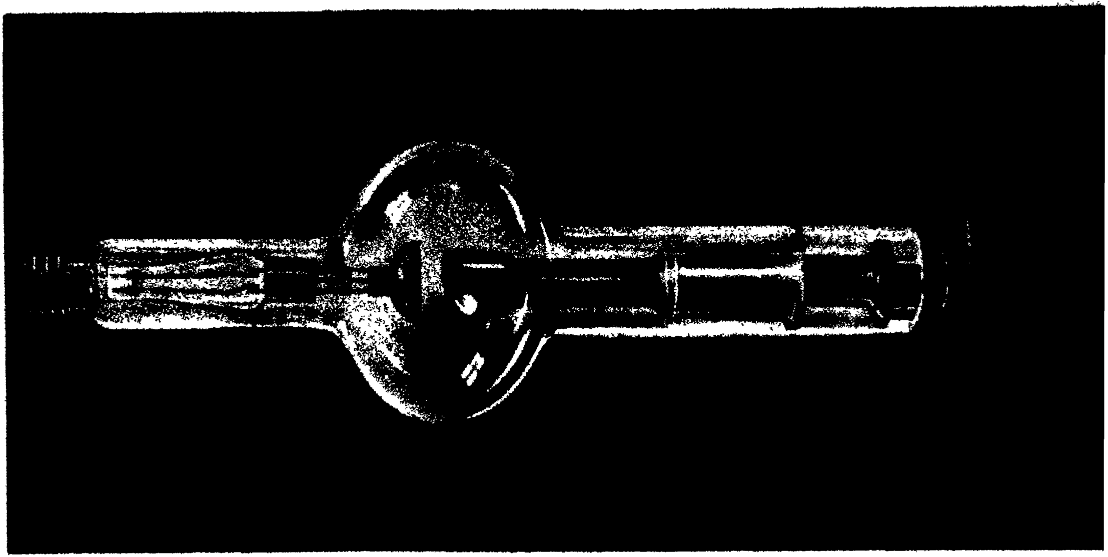

FIG. 25. Coolidge X-ray tube, with thick copper anode-stem and radiator for cooling the target. The spiral cathode is enclosed in a hemispherical sheath of metal

has assumed great importance in wireless telephony, as we shall see in due time. It was already known that a strongly-heated metal gave off electrons. These ordinarily exist as free electrons in the metal, and to them its conductivity is due. They also play a part in the conduction of heat, which they convey from point to point in the metal by their collisions with the atoms. When the metal is raised to a sufficiently high temperature their movements become so violent that many of them escape altogether into the surrounding space. Here, then, is the source of electrons made use of in the Coolidge tube. The cathode is made in the form of a spiral of wire which can be strongly heated by means of a current supplied by a subsidiary battery. In order to cause these electrons to pass with the requisite velocity to the target it is only necessary to connect up the cathode and target (which also acts as anode) to a powerful 'high voltage' source of electricity, just as is done with an ordinary discharge tube. In such a case no gas is needed in the tube; for the supply of electrons is obtained independently by means of the hot cathode; the presence of gas would, indeed, be an obstruction rather than a help. This form of tube has the advantage that the quantity of electrons evolved can be regulated at will by altering the temperature of the cathode, and their velocity by altering the main high voltage supply; thus the output and penetrating power of the X-rays, which depend on these factors, can be adapted to any particular purpose for which they are to be employed. It is necessary to adopt special means for cooling the target, which would otherwise be speedily burnt out under the bombardment of electrons which it sustains.

Shadow pictures. X-rays are chiefly useful in obtaining shadow pictures of things inaccessible to ordinary light and vision. Just as a lighted candle will throw a shadow of an opaque body on to a white screen, so will a beam of X-rays project a shadow of an

FIG. 26. The author's pen pauses a moment to be X-rayed

object, placed in its path, provided the object is opaque to the rays. But as X-rays are not visual rays, it would be useless to throw this shadow on (say) a screen of white paper, for no visible effect would be produced. Two methods are available for rendering it visible. First, a paper screen may be covered with a layer of fluorescent substance; then, where the X-rays fall, a bright illumination will be observed, the shadows being left dark. It is preferable to coat the back of the screen, and to observe the effect from that side (the rays of course penetrate the paper freely), so that the object can be held close to the other side, and a sharp shadow obtained. The hand forms an interesting object for 'screening'—the bones, on account of their much greater opacity to the rays, appearing in remarkable contrast to the faint outline of the flesh.

A less spectacular method, but a more generally useful one, is to substitute a photographic plate for the fluorescent screen. After exposure to the rays, with the object interposed, the plate is developed, and the shadow picture preserved in permanent form. The frontispiece shows an X-ray installation used for purposes of demonstration. The target from which the rays proceed can be seen in the centre of the globular 'tube'. With this apparatus the photograph, Fig. 26, was taken.

Fig. 27 is reproduced from a photograph kindly given to me by Dr. Rupert Hallam, of Sheffield, and taken in the ordinary course of X-ray diagnosis. It gives two views of a double fracture of the leg.

Another example of X-ray work is given in Fig. 28. This is a stereoscopic slide of shrapnel embedded in a jaw-bone. It can be seen in high relief by means of a stereoscope; or (after a little practice) by merely holding the slide about 24 inches from the eyes, and, after fixing the eyes on the middle of the black band between the views, withdrawing the vision to a point about midway between the eyes and the slide (or 'squinting') so as to cause the two views to coalesce. The black crosses are location

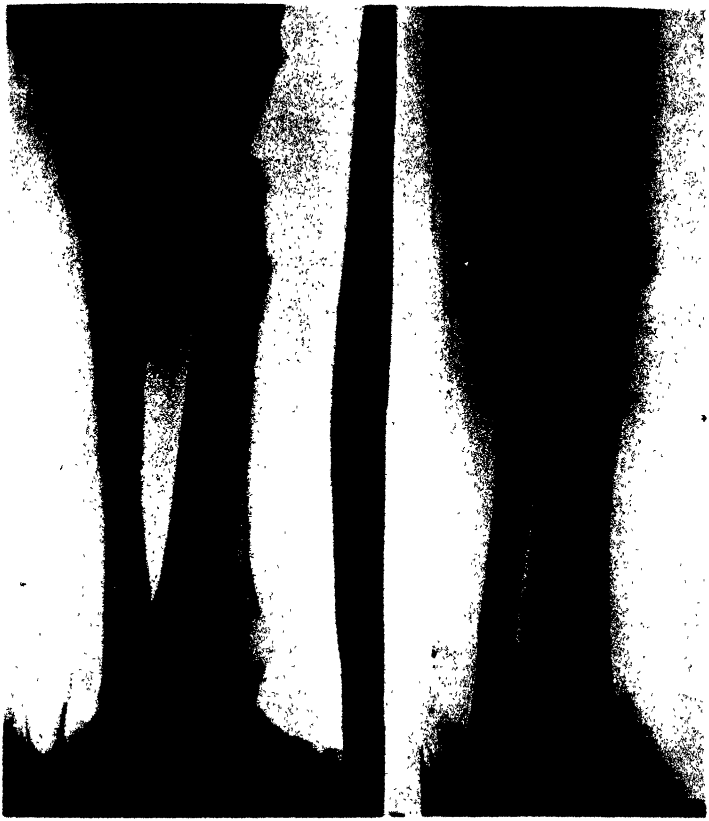

FIG. 27. X-ray photographs of a broken leg

marks of sheet lead fixed with plaister to the outside of the patient's jaw. The double photograph was taken and the foreign bodies located during war service by my colleague, Professor S. R. Milner, to whom I am indebted for the slide. The shrapnel was afterwards successfully extracted.

Not only can such obvious things as fractures, and the presence of foreign bodies, such as bullets and fragments of shrapnel in war time, be accurately located; but various diseases of the bone can be detected; and abnormalities of the heart and some other organs, which, owing to their somewhat greater density than the other tissues, are capable of throwing shadows, can be noted. The digestive system can be examined and the passage of food watched if carbonate of bismuth, or some other substance opaque to the rays, is mixed with the meal. The rays are extremely valuable in the diagnosis, especially in its earliest stages, of tuberculosis of the lungs—a condition which gives rise to a reduction in the transparency of the tissues affected.

The applications of X-rays to industrial and other purposes are numerous and varied in the extreme. The more penetrating rays are used for the detection of defective welds in steel plates, and internal flaws in metal generally. Unevenness in the distribution of the component metals in an alloy can be detected; likewise faults in construction of hidden parts of metal or wooden structures. The contents of packing cases have been checked (without opening them, of course); the cores of golf balls examined; oysters searched for pearls without opening the shells; false jewels differentiated from genuine ones (the transparency to the rays being different); moths detected in tobacco destined for the manufacture of cigars; fresh eggs distinguished from stale; the interior of fossils examined; the internal structure of living plants observed; 'fake' old masters and antiques exposed; ancient manuscripts and palimpsests examined.

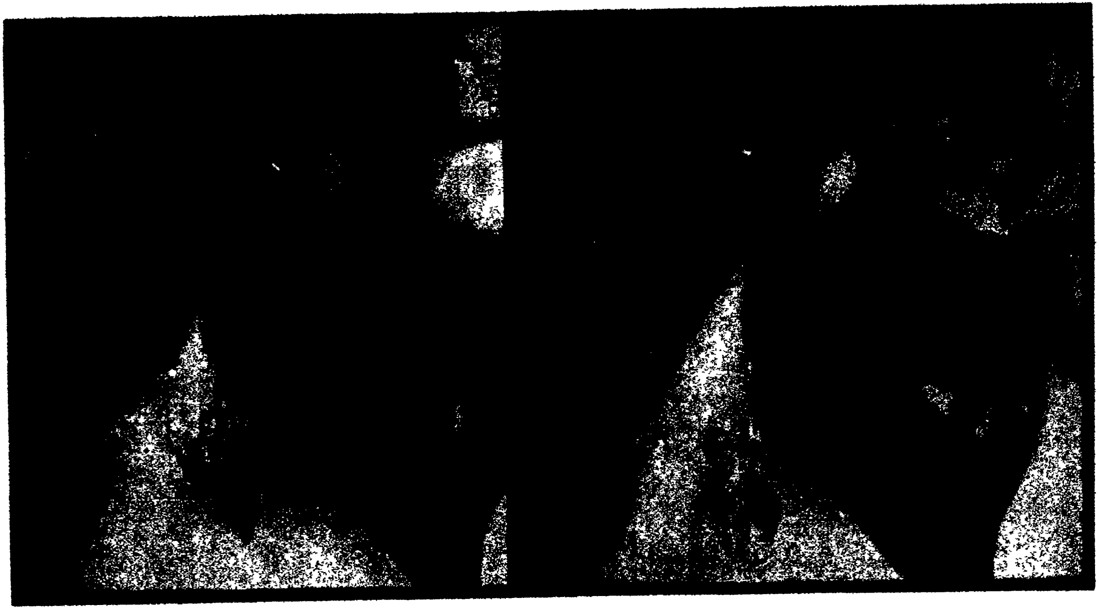

FIG. 28. Stereoscopic view of shrapnel embedded in jaw-bone, showing location marks affixed to the outside of the patient's jaw

Apart from these and many other applications which depend on the formation of shadow pictures, the X-rays and also the rays from radium produce important physiological effects—some harmful and some beneficial. The dangerous properties of the rays are not a little aggravated by the insidious nature of their action. Serious effects may be produced by exposure of the skin to the rays, though these effects may not become evident until days or weeks after the exposure has taken place. So-called 'burns' are produced; and if exposures are continued, dermatitis—which has in many cases proved fatal—or cancer may supervene. It is obvious that workers with radium or X-rays should take all possible precautions against exposure, by the use of protective screens, whenever it is necessary to be near the source of the rays.

Nevertheless, the rays have valuable properties in the treatment of malignant diseases. The cells of which healthy tissues are composed have more power of resisting the action of the rays than malignant cells, which tend to disappear under treatment. Clearly, it is essential that the 'dose' administered should be so chosen as to produce the greatest benefit possible without at the same time injuring the healthy cells—by no means an easy matter. The treatment has proved successful in cases of rodent ulcer and the like; and it is very useful in many skin diseases. Good results have been obtained in the treatment of ringworm; but overdoses may produce baldness.

Radium has a marked effect on plant life. Small doses of the rays produce a distinct improvement in the growth of young plants; large doses, on the other hand, are highly prejudicial. With rays of great intensity seeds and bacteria can be killed. At one time a mild sensation was produced by the announcement that spontaneous generation of life had been brought about by the rays of radium—this, however, was the result of an 'experimental error'.

Light

We now turn to the rays of the ordinary spectrum, visible and invisible. Radiation of this kind reaches us from the sun; and while the excitation of vision may be regarded as its most remarkable manifestation, we must not forget that the heating effect produced is essential to the habitability of the earth. All the waves participate in this effect, but only a few of intermediate length are able to excite vision. The totality of the visual rays from the sun give rise to the sensation 'white'; but when selected wave-lengths only reach the eye, colour sensations, depending on the particular selections, are produced. Many ordinary objects, receiving the light of the sun, absorb certain constituent waves—to which their atoms respond—and reflect or transmit the rest. If these rejected portions reach the eye, the object from which they proceed is seen as a 'coloured' object. The colour sensation is, of course, purely subjective—nothing like 'red' or 'blue' exists in the object itself, only a particular species of vibration dependent on its constituent atoms.

Composition of heavenly bodies. The light from the sun enables us to determine, partially at least, the chemical composition of that body. Just as different coloured glasses absorb definite constituents of white light and allow others to pass through, so layers of vapour in the atmosphere of the sun are capable of absorbing certain constituents of the white light given off by his incandescent surface, and of transmitting the remainder. For this reason, the light which reaches us from the sun is found to be deficient in many wave-lengths. The solar spectrum is crossed by narrow gaps or dark 'Fraunhofer' lines, so named from their discoverer,[1] each of these indicates exactly the position of a missing constituent of the original light. Now, the vapour of a given element will, if rendered incandescent, emit just those wave-lengths which it is itself capable of absorbing; for, whether emitting or absorbing, it confines its activity to the particular waves which correspond in frequency to the vibrations of its own atoms. If, then, by locating the Fraunhofer lines, we ascertain which wave-lengths are missing from the solar spectrum, and find that these coincide exactly with the wave-lengths emitted (as line spectra) by incandescent vapours prepared in the laboratory, we are justified in concluding that identical vapours exist in the atmosphere of the sun. In this way many of the chemical elements were detected in the composition of the sun; but some of the Fraunhofer lines could not be identified as belonging to any known terrestrial substance. Clearly, therefore, the sun contained an element new to chemistry—it was given the name 'helium'. It has since been discovered on the earth; and it figures largely in our sketch of the constitution of the atom.

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[1] J. von Fraunhofer (1787–1826), professor and optician at Munich.

The Brownian movement. The observation of very small objects by the microscope is largely influenced by the effects of diffraction; so that it is impossible, whatever the so-called magnifying power of the instrument may be, to distinguish the shape, or any of the details of an object of less than a certain size. The existence of very small isolated particles can, however, be detected; when properly illuminated they appear as bright points of light. This is due to the fact that each particle scatters the light falling on it, and some of this light reaches the eye through the microscope. The apparatus used in these observations is called the 'ultra-microscope'; its peculiarity really lies in the means adopted for illuminating the particles. The illumination is so arranged that all light except that scattered by the particles is excluded from the eye. Fine solid particles of suitable size, suspended in water, and indistinguishable by ordinary means, are seen by the ultra-microscope to be in perpetual and rapid motion—each particle following an irregular zig-zag path, as though buffeted continually by some unseen agency. This movement, discovered by Robert Brown (1773–1858), an eminent botanist, and known as the 'Brownian movement', is actually due to such a buffeting by the molecules of the surrounding water, which are themselves invisible even through the ultra-microscope; the observation thus helps to verify our theory of the constant agitation of the particles of matter.

The colour of the sky. But even molecules themselves can scatter light; and though we can never hope to see a molecule in the sense of observing its shape or structure, we have nevertheless in the light of the sky an example of the effect of the scattering of light by molecules of air. On account of their small size the molecules tend to scatter the shorter waves of light more freely than the longer ones; this fact accounts for the blue colour of the sky—one of the great mysteries of nature until comparatively recent times.

Hertzian Waves

Varied as are the properties and applications of the electro-magnetic waves of which we have given this slight sketch, we have as yet by no means exhausted the known series of such waves. None of those we have dealt with have a length of more than about one-eightieth of an inch. They are all emitted by the atoms of matter. But if we turn our attention from individual atoms, and consider the flow of electrons which constitutes an electric current, we are led to inquire whether such electronic movements could give rise to the emission of waves. Remembering our analogy of the production of ripples by the rapid to and fro movements of a rod dipped into water, we see that no emission could be expected unless the electrons were made to move rapidly backwards and forwards in the circuit. This means that the current must flow first in one direction and then in the other—that it must ' alternate ' or ' oscillate '.

Confirmation of Maxwell's theory. Waves generated by this means were observed in 1888 by Hertz (1857–94) of Hamburg. Hertz's experiments were of the greatest importance from a scientific point of view, in that they gave striking confirmation of the electro-magnetic theory of light which had been enunciated by Maxwell. True, the waves he produced were enormously longer than light waves—it is calculated that his original apparatus gave waves 5 or 6 yards long—but they were clearly of electrical origin, and conformed with the requirements of Maxwell's theory. Their great length was of course due to the comparative slowness of the oscillations which generated them. These oscillations were produced by a spark discharge between two metal conductors, which were highly charged with positive and negative electricity respectively. When the spark passed between the conductors a reverberative effect took place, as if the electricity, in suddenly bridging the gap, rushed across with great violence and rebounded to and fro, till at last its energy was frittered away. This surging backwards and forwards of the electricity gave rise to waves which spread out from the ' oscillator ', as the apparatus was called, into the surrounding space.

In order to detect the presence of these waves at a distance from the oscillator, Hertz used a ' resonator ', consisting of a copper rod bent into the form of a hoop, the ends of the rod being brought close to one another but not actually into contact. When this was held opposite the oscillator, in the path of the waves, electric currents were set up in it; and these manifested their presence by minute sparks which passed across the gap between the ends of the rod. In spite of the great length of these waves they behave in some respects like light waves. They can be reflected by a large metal plate as light is reflected by a mirror; and other experiments can be made to show that the two classes of waves are essentially similar.

The shortest of the Hertzian waves which have been produced are about one-sixteenth of an inch long; so that a gap exists between the longest known infra-red and the shortest Hertzian. Apart from this, we have experimental knowledge of the whole series of electro-magnetic waves from the shortest gamma-rays, of which about 25,000,000,000 go to an inch, to the extremely long waves of the Hertzian range which, with similar waves to which we shall presently more particularly refer, extend to a length of tens of thousands of yards.

The germ of wireless. The experiments of Hertz formed the starting point of a series of investigations which have culminated in long distance wireless telegraphy. Hertz's oscillator and resonator really constituted a short distance wireless telegraph, which involved the fundamental principles of present-day practice. We shall consider briefly the remarkable modern adaptation of these principles to wireless telephony, in which waves of various lengths are employed ranging, for the British stations, from about 300 to 500 yards.

Wireless

Before dealing with the production and reception of the waves used in wireless telephony it may be well to explain a few terms commonly met with in that connexion.

(*a*) *The Thermionic Valve.* One type of valve, with its evacuated glass bulb and fittings, is shown in Fig. 29. *A* (see diagrammatic inset) is a cathode consisting of a thin wire, and generally known as the ‘ filament ’. This can be raised to incandescence by means of the battery *D*; in this condition, like the hot cathode of the Coolidge X-ray tube, it emits a copious supply of electrons. *B* is a ‘ plate ’ which forms the anode of the valve.

Suppose the anode and cathode to be connected up to a battery of many elements or cells as shown at *E*; then the anode, being positive, will attract the electrons given off by the filament; and thus a constant stream of electrons will flow across the gap from *A* to *B*. This constitutes a current of electricity, and this current will pass right round the circuit *BAEB*, which circuit is called the ‘ plate circuit ’. So far the action is exactly similar to that of the Coolidge tube; but an additional feature is introduced in the valve at *C*, and is known as the ‘ grid ’. The function of the grid, which is merely an open mesh or spiral of wire, is to act as a kind of controller of traffic between the filament and the plate. To make it operate, it must be connected to a circuit, called the ‘ grid circuit ’, in which fluctuations of current take place. We will not trouble for the moment how these fluctuations are produced, but will note the fact that as they occur the grid will receive alternately positive and negative charges of electricity. Now, when the grid is positive it will help the flow of electrons in the valve by attracting them from *A*; but when it is negative it will hinder the flow by repelling the electrons (which would otherwise stream from *A* to *B*) back towards *A*. On account of the proximity of the grid to the source *A* from which the electrons emerge, it exercises a great influence upon them, and is able, by very small fluctuations in its own circuit, to produce large variations in the supply of electrons reaching *B*, and, consequently, to produce large variations in the current flowing round the plate circuit. Thus: Small variations of current in the grid circuit produce large variations of current in the plate circuit. . . . (I).

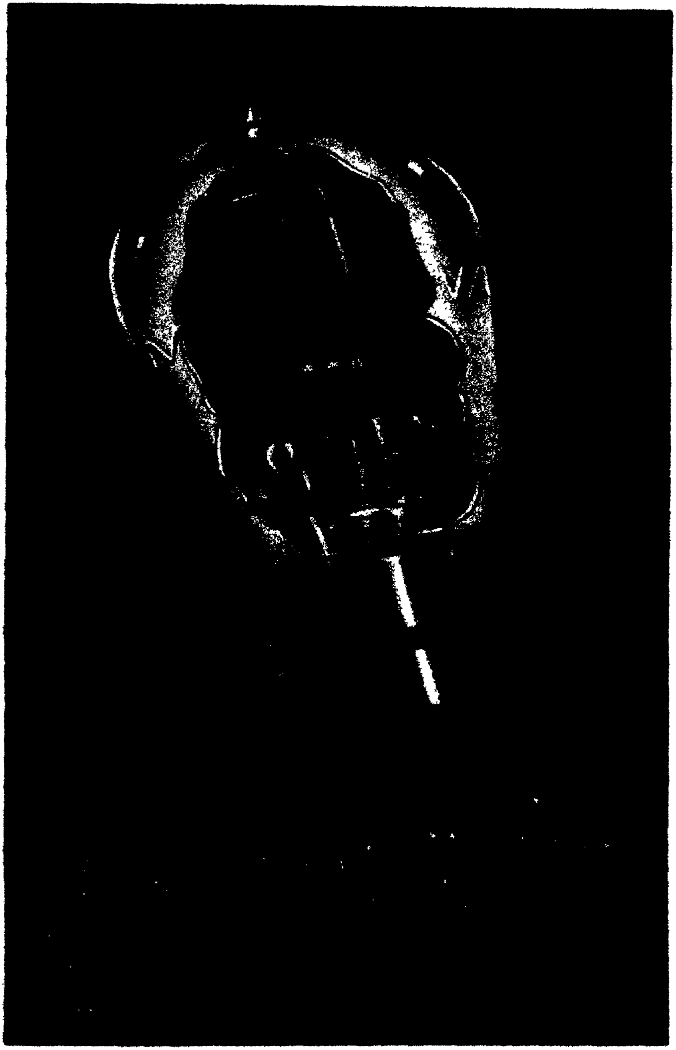

Fig. 29. Thermionic valve

(*b*) *An Oscillating Circuit.* A current of electricity in a wire consists of a flow, along the wire, of a stream of free electrons. In some circumstances the electrons, instead of flowing steadily along, surge to and fro in the wire, as the air surges to and fro in a sounding organ pipe; the circuit is then said to 'oscillate'. Every circuit has a natural frequency with which these oscillations can most readily take place—by 'frequency' of course we mean the number occurring per second. The technicalities of the subject we will leave alone, and simply think of an oscillating circuit as one in which electrons surge to and fro with the natural frequency of that circuit. . . . (II).

(*c*) *Coupling.* Two circuits may be 'coupled' by including in each circuit a coil of wire, and placing these coils near to one another, but without actual contact. Then, if oscillations occur in one of the circuits, the coil of that circuit will set up a fluctuating magnetic field in its neighbourhood; this will act on the coil of the other circuit and produce in it oscillating currents similar to those in the first circuit. (The process is evidently based on the observations of Oersted and Faraday to which we referred in Section I). Thus: When two circuits are coupled oscillations in either of them will produce corresponding oscillations in the other. . . . (III).

For the proper working of this arrangement the two circuits should be 'tuned' to unison; that is, their natural frequencies of oscillation should be made identical. The means of doing this we shall not dwell upon.

Waves suitable for wireless telephonic transmission are similar to light waves, but immensely greater in wave-length and less in frequency. They are produced by the oscillations of electrons in a long wire or 'aerial'. Different methods may be adopted for producing the oscillations; we shall consider one method only.

Generation of the waves. Suppose we have a valve, complete with plate circuit and grid circuit. Without going into the details of these circuits, we will assume that they are 'coupled', and that their 'natural frequencies' are identical. All being adjusted, let us suppose (what is sure to happen in practice) that minute accidental oscillations occur in (say) the grid circuit. At once a kind of reciprocal action begins to take place between the two circuits, on this wise: the small oscillations of the grid cause larger oscillations in the plate circuit, cf. (I); these in turn, by virtue of the coupling of the circuits, react on the grid circuit and reinforce its oscillations (III); these reinforced grid oscillations produce still stronger oscillations in the plate circuit; and so on, till in a very short time, by repeated action and reaction between the two circuits, the oscillations reach the maximum intensity of which the system is capable. The system is, in fact, what we may describe as an automatic oscillator. Let us see how we can apply it to our purpose.

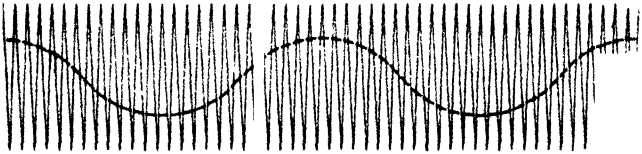

FIG. 30. A train of regular waves

Suppose we couple it to a long wire or 'aerial'. It will cause, by (III), oscillations in this; that is, it will cause electrons to surge to and fro in it. These surging electrons will generate waves, like extremely long light waves, which will travel outward into the surrounding space. We may represent them by the firm line in the adjoining figure; they are regular and enormously rapid.

The dotted line represents for comparison a sound wave which corresponds to the sound we wish to transmit. Its frequency is vastly less than that of the electro-magnetic wave; this is indicated slightly by drawing a number of the latter waves to one of the former. We may look upon the regular electro-magnetic waves, travelling to the distant station, as forming a sort of line of communication between the speaker and the listener. Now, electromagnetic waves are not sound waves, and therefore they cannot carry sound; but they may be so modulated as to simulate sound waves, and these simulated sound waves can be translated into actual sound waves at the distant station. How can this be done?

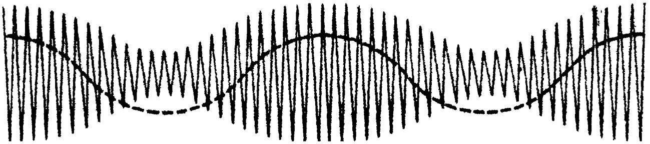

FIG. 31. Modulated waves

Modulation of the Waves. Consider first the transmitting apparatus. The oscillations given by the valve system are continuous and regular. But instead of coupling it with the aerial, let us couple it with a circuit containing a microphone. We know (p. 48) that if we speak to a microphone its resistance varies every time a sound wave falls upon it. Now, while we speak, the microphone circuit is oscillating; that is, currents are rapidly passing to and fro in it; but these currents will vary in intensity each time its resistance is altered; for the greater the resistance the smaller the current, and vice versa. Thus, the oscillations in the microphone circuit vary in intensity in exact conformity with the waves of the spoken sounds. We have now obtained the modulated oscillations we require, and it only remains to couple this microphone circuit with the aerial, in order that they may be transmitted through space in the form of waves. Waves of this kind are represented by the firm line in the accompanying diagram, in which the corresponding sound waves are also indicated.

To sum up: the oscillator gives out a series of regular oscillations; these are received by the microphone, and modulated in conformity with the spoken sounds; the modulated oscillations are passed on to the aerial which transmits them through space in the form of modulated electro-magnetic waves, or, as we have called them, simulated sound waves.

The reader will understand that this brief sketch of telephonic transmission is only intended to give a general idea of the principles involved; and that it is in no sense a detailed description of actual wireless practice.

Reception of the waves. It now becomes necessary to consider how the electro-magnetic waves can be reconverted into sound waves at the receiving station. The first requirement is an aerial having a natural frequency equal to that of the on-coming waves—a condition obtained by 'tuning'. When the waves impinge on this they set into motion its free electrons, as sea waves might set swinging up and down a row of corks on a fisherman's net. The oscillations in the aerial will correspond with the modulated waves which we have illustrated in the firm line of Fig. 31.

Suppose we connect a telephone to the aerial—can we expect this to give out the required sounds? Let us consider what would happen. Currents would tend to flow backwards and forwards in the telephone circuit with the frequency of the oscillations. Now, in the first place, this is not the frequency of the required sound, but is a far higher frequency; and in the second place, a telephone is utterly incapable of responding to oscillating currents of such frequency. But if we can cut out (say) all the 'backward' currents, and retain in the circuit only the 'forward' ones, the effect will be different. For now the currents in the telephone will all be in the same direction, instead of being alternately in opposite directions; and as these currents pass in groups (*A*, *B*, *C*, Fig. 31) the general effect will be that each group of individual currents will act like a single current (as a rapid series of blows tends to act like a single heavier blow), and these single currents will pass through the telephone with the frequency of the sound to be reproduced. The telephone, therefore, will repeat the sounds which were spoken to the microphone at the transmitting station.

We need, then, a means of suppressing all the backward currents (as we have called them) in the telephone circuit, while allowing all the forward currents to pass; or, as it is called, of 'rectifying' the oscillations. The simplest way is to insert a 'crystal detector' in the circuit. This consists of a crystal (say of carborundum) lightly touched by a fine wire—an arrangement which has been found by experiment to allow currents to pass in one direction only. This method will answer its purpose if the on-coming waves are powerful enough to ensure the vigorous working of the telephone, and so cause it to give out a sufficiently loud sound; if not, a more complicated receiving apparatus is necessary. I do not propose to deal in any detail with this, but we may note one or two points of importance. First, a valve can act (like the crystal) as a rectifier; because the current between *A* and *B* (Fig. 29) can only pass one way; for only *A* can emit electrons. The usual method of using the valve for purposes of rectification is, however, rather complex, and need not be entered into here.

Amplification. Another important point is that a valve, or a series of valves, can be used to 'amplify' oscillations which are too feeble to operate the telephone with the necessary energy. We know that an oscillation in the grid circuit produces a more intense oscillation in the plate circuit. If, then, the feeble oscillations be applied to the grid circuit, those produced in the plate circuit will be stronger. This plate circuit may be coupled with the grid circuit of a second valve, whose plate circuit will then respond with oscillations of still greater intensity. This process of amplification can, if necessary, be carried on through several valves, as in the case, for instance, of the reception of signals from a very distant station. Some enthusiastic listeners-in have actually tried, with a long series of valves, to detect signals from the planet Mars!

VI

Atomic Aggregates

Molecules. We have dealt hitherto with electrons and atoms, and with the various types of radiation which they emit. We have not considered the question of the combination of atoms in the formation of molecules. Ordinary hydrogen gas (for instance) is made up, not of single isolated atoms, but of pairs of atoms, each pair constituting a molecule of hydrogen. Chlorine gas is similarly compounded of molecules, each comprising two chlorine atoms. But these molecules can, unlike their constituent atoms, be split up by ordinary chemical means. A jet of hydrogen may be made to burn in an atmosphere of chlorine; the result will be the formation of new molecules, each consisting of one atom of hydrogen and one of chlorine. The hydrogen and chlorine molecules are in this way split up, and the atoms are re-arranged to form molecules of a new compound called hydrochloric acid. The atoms thus preserve their identity; when two atoms combine to form a molecule the union is not so close as to make them form a single atom. This is explained by the assumption that, in the molecule, the nuclei of the constituent atoms do not merge into a single nucleus; if they did so we should have to recognize that a new atom had been formed.

With regard to the molecule of hydrogen, the simplest supposition is that the two protons or nuclei form the ends of an imaginary axis about which the two electrons revolve; the relative positions being such that the attractions between the protons and electrons exceed the repulsions between the two protons and between the two electrons; so that the molecule holds together as a whole. An analogous but more complicated arrangement would exist in the case of the molecule of chlorine.

Compounds. In considering the formation of compounds like hydrochloric acid it will be convenient to refer to a theory propounded by Bohr, in which he concluded that the extra-nuclear electrons of atoms tend to arrange themselves in layers or rings, each containing a definite number of electrons. The first ring, according to this theory, contains two electrons (except, of course, in the case of hydrogen which has only one), and the second, when complete, 8 electrons. The third ring also contains 8 electrons, except when the total number of electrons in the atom is greater than 18—but we will, for the sake of simplicity, leave these heavier atoms out of our consideration.

The elements which have their rings completely filled, according to this scheme, are (omitting the heavier elements) helium, neon, and argon, with 2, 10, and 18 electrons respectively; these being the atomic numbers of these elements. The first has 1, the second 2, and the third 3 complete rings of electrons. Now, these elements are distinguished chemically from the others by reason of their inertness—they form no chemical compounds whatever. Their atoms are complete in themselves, and have no tendency to join with other atoms.

Chemical affinity. Now, consider the case of chlorine. This element has atomic number 17; its 17 electrons must be arranged on three rings—2 on the first, 8 on the second, and 7 on the third. The third ring is thus incomplete to the extent of one electron. In this condition the atom is, of course, neutral; but it has a tendency to complete its outer ring by the inclusion of an additional electron. Now, a hydrogen atom has a single electron, and so the two atoms, chlorine and hydrogen, manifest an affinity for one another, and readily combine. Again, the atom of sodium (atomic number 11) comprises 2 electrons in its first ring, 8 in the second and a single one in the third. This atom also readily combines with chlorine, which requires the odd electron to complete its third ring. In this way sodium chloride (common salt) is produced.

The molecule of water contains one atom of oxygen (atomic number 8) and two of hydrogen. The oxygen atom has 2 electrons in its first ring and 6 in its second: hence its affinity for two hydrogen atoms which can supply the two electrons necessary for the completion of its second ring.

Crystals

Crystal structure. A crystal has been likened to a huge molecule, which may contain many millions of atoms arranged symmetrically on a definite plan—a symmetry which accounts for the regular shape of the crystal. In dealing with Moseley's work on X-rays we had occasion to refer to the use of crystals in the determination of X-ray wave-lengths. Much work of a complementary kind—

the investigation of crystals by means of X-rays—has been done by W. H. and W. L. Bragg. The principle of the method employed is analogous with the one we described on p. 80, where we considered light waves as represented by a column of men marching in regular formation through openings in a wall. A somewhat different manœuvre by the column of men may serve to illustrate this case. Suppose the men, marching across open country, approach obliquely a regular plantation of trees, very openly spaced, as indicated by dots in the figure. When a man reaches a tree he immediately turns through a definite angle, and thereafter keeps straight on. The paths of three individuals are shown in the figure. Now, it turns out that if the angle described by the men is correctly chosen, they will all emerge from the wood in

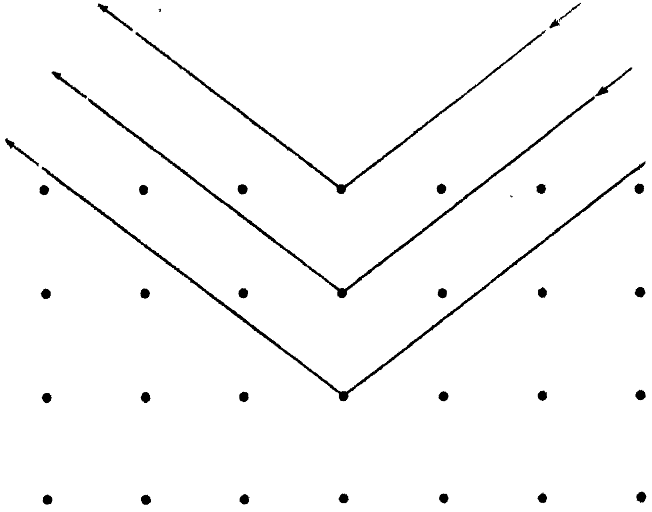

Fig. 32. To illustrate the reflection of X-rays by a crystal

regular formation; though the particular individuals marching abreast will not be the same as before. The correct angle will depend on the distance between successive rows of trees; and, given this angle (and the distance between the rows of men) it becomes possible to calculate the distance between the rows of trees.

Now replace the trees by the atoms of a crystal, and the column of men by a beam of X-rays of known wave-length; it will then become possible, by measuring the angle at which the rays are regularly reflected by the crystal, to determine the distance between successive rows or layers of atoms in the crystal. (Incidentally, it is of interest to note that X-rays can be reflected by a crystal—though not, like ordinary light waves, by an ordinary mirror, or by a plate of glass. By comparison with a crystal, a plate of glass is a highly irregular structure, and the minute waves of the X-rays cannot be reflected from it with anything in the nature of a 'regular formation'. When considered with reference to the much longer light waves, however, the surface of well-polished glass is comparatively smooth, and regular reflection can therefore take place.)

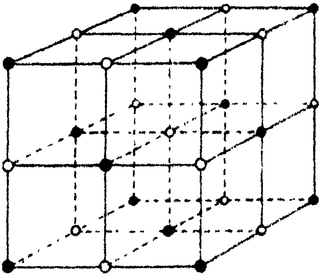
FIG. 33. Model of small portion of a crystal of rocksalt. The black and white circles represent atoms of sodium and chlorine respectively.

By using the method of X-ray reflection, the arrangements of the atoms in many crystals have been determined. In crystals composed of different kinds of atoms, as rocksalt—which consists of equal numbers of atoms of sodium and chlorine—it has been found possible to assign places to the different kinds. This differentiation is possible because the heavier atoms reflect the rays more copiously than the lighter ones. The result in the case of rocksalt is very simple; the atoms of sodium and chlorine are arranged alternately at the corners of imaginary cubes packed together like a pile of bricks.

These researches have inaugurated what practically amounts to a new science. Into this we cannot enter; but enough has perhaps been said to exhibit the fundamental nature of electricity and its applicability to subjects with which, at first sight, it might appear to be quite unconnected.

GLOSSARY OF TERMS

N.B.—These definitions are not intended to be exhaustive, their purpose is merely to help the reader to keep in mind the meanings of terms which he has already found explained in the text.

Alpha-rays : consist of positively charged particles (helium nuclei) emitted by radio-active substances.

Ampere : the practical unit of current.

Anode : see Electrode.

Atomic number : a number representing the position of an atom in the series of elements according to Moseley's classification. It is also equal to the nuclear charge of the atom expressed in protons.

Atomic weight : a number which is proportional to the weight of an atom, the weight of the atom of hydrogen being taken (to a close approximation) as unity. But in the case of an element with isotopes the atomic weight generally represents the average weight of the atoms present in a quantity of the element, the atomic weights having been obtained and tabulated before isotopes were discovered.

Beta-rays : consist of negatively charged particles (electrons) emitted by radio-active substances.

Cathode : see Electrode.

Cathode rays : rays, consisting of electrons, emitted by the cathode in a discharge tube.

Conductor : a body or substance through which electricity can flow.

Coulomb : the practical unit of quantity of electricity.

Electrics and Non-electrics : old names for non-conductors and conductors of electricity.

Electrode : a plate or wire by which an electric current enters or leaves a discharge tube or other piece of apparatus. The electrode by which the current enters is called the *anode*, and that by which it leaves the *cath*

Electrolysis : the process of decomposition of a substance by the passage of an electric current.

Electrolyte : a substance which is decomposed or decomposable by the passage through it of an electric current.

Electro-magnetic Waves : the term includes the whole range of waves of electrical origin from the gamma-rays to the long 'wireless' waves.

Electromotive Force : that which moves or tends to move electricity.

Electrons : negative particles which exist as constituents of atoms, and also in the free state as beta-particles, cathode rays, &c.

Elementary Positive and Negative charges : charges equal to those of the proton and electron respectively.

Field, Electric or Magnetic : a region pervaded by electric or magnetic forces. In an *Electro-magnetic Field* both kinds of force are present.

Frequency : number of vibrations (or of waves emitted) per second.

Gamma-rays : rays, consisting of waves of extremely short wave-length, emitted by radio-active substances.

Induction : the action of charged or magnetized bodies, or of electric currents, on neighbouring bodies, without direct contact.

Insulator or Non-conductor : a body or substance through which electricity cannot flow.

Ions : charged particles such as those which take part in electrolysis and those concerned in the conduction of electricity through gases. Ions may be produced in gases by the passage of X-rays or other *ionizing* agents.

Isotopes : atoms with different atomic weights but identical chemical properties, so called because they occupy the *same place* in the classification of the chemical elements.

Lines of Force : imaginary lines indicating the direction of electric or magnetic force in a field.

Nucleus : the central part of an atom.

Ohm : the practical unit of resistance.

Positive Rays : consist of positively charged particles. They are produced in a discharge tube having a perforated cathode.

Proton : the positive nucleus of the hydrogen atom. Also used as a measure of the positive constituents of the atoms.

Radio-activity : the property of spontaneous emission of rays possessed by certain substances.

Resistance : the resistance offered by a conductor to the passage of electricity.

Spectrum : a succession of colours produced by splitting up light into its constituents. The term is extended to include invisible regions on both sides of the visible spectrum, these being due to non-visual radiation.

Vitreous and Resinous Electricities : the two species of electricity, usually known as positive (+) and negative (−) respectively.

Volt : the practical unit of electromotive force.

Wave-length : the distance from any part of a wave to the corresponding part of the next in a series of waves—as from crest to crest in sea-waves.

X-rays : consist of waves of extremely short wave-length.

SELECT LIST OF BOOKS

For more detailed information on electricity in general, see
Elementary Lessons in Electricity and Magnetism (new edn.), by Silvanus P. Thompson (Macmillan),
or any good text-book may be consulted.

The following books on special subjects may also be consulted :
Atomic Theories, by F. H. Loring (Methuen).
Atoms and Rays, by Sir Oliver Lodge (Benn).
Atoms and Electrons, by J. W. N. Sullivan (People's Library, Hodder & Stoughton).
Electrons and Ether Waves, by Sir W. H. Bragg (Oxford University Press).
The Atom and the Bohr Theory of its Structure, by H. A. Kramers and Helge Holst (Gyldendahl).
The Electron, by R. A. Millihan (University of Chicago Press).
Ions, Electrons, and Ionizing Radiations, by J. A. Crowther (Edward Arnold).
Isotopes, by F. W. Aston (Edward Arnold).
Radioactivity and Radioactive Substances, by J. Chapman (Technical Primer Series, Pitman).
X-rays, by G. W. C. Kaye (Longmans, Green).
X-rays and Crystal Structure, by W. H. and W. L. Bragg (G. Bell).
Radium, X-rays, and the Living Cell, by Colwell and Russ (G. Bell).
The Industrial Applications of X-rays, by P. H. S. Kempton (Technical Primer Series, Pitman).
Electrons, Electric Waves and Wireless Telephony (Royal Institution Christmas Lecture), by J. A. Fleming (Wireless Press).
The Oscillation Valve, by R. D. Bangay (Wireless Press).

Practical applications of Electricity are dealt with in
Science in the Service of Man : Electricity, by S. G. Starling (Longmans, Green),

and a sketch of modern ideas in Physics in
The New Physics, by A. Haas, translated by R. W. Lawson (Methuen).

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Printed in England at the Oxford University Press